



**SUSTAINABLE ENERGY TRANSITION AND
OPTIMIZATION OF GRID
ELECTRICITY GENERATION AND SUPPLY**

BY

Moses Jeremiah Barasa Kabeyi

**Thesis submitted in fulfillment of the requirements for the award of the degree of Doctor
of Engineering in the Department of Industrial Engineering, Faculty of Engineering, and
the Built Environment at Durban University of Technology.**

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PREFACE

This doctoral study was undertaken in the department of Industrial Engineering, Faculty of Engineering and Built Environment of Durban University of Technology, South Africa. The research involved investigation of the sustainability of energy sources, power plants and energy conversion systems for power generation as well as technologies and concepts that will enhance the global energy transition which seeks to realize the global commitment to sustainably achieve net zero emissions to limit energy-related greenhouse gas emissions and related global climate change. This thesis has 22 chapters compiled and discussed with references to the author's related published and unpublished research papers in the form of book chapters, conference papers and journal papers.

DECLARATION

I, Moses Jeremiah Barasa Kabeyi, the undersigned candidate, declare that.

- (i) The research reported in this thesis, except where otherwise indicated, is my original work.
- (ii) This thesis has not been submitted for any degree or examination at any other university.
- (iii) This thesis does not contain other persons' data, pictures, graphs, or other information unless specifically acknowledged as being sourced from other persons through citation.



Sign: Date: ...03/01/2024.....

As the candidate supervisor, I do agree to the submission of this thesis.

Prof. Oludolapo Akanni Olanrewaju

Sign:...Date: 05/04/2024.....

DEDICATION

This thesis is dedicated to my late father Christopher Kabeyi Wakameri who passed on 1/12/2021 just a year into my doctoral research. Before I departed for South Africa to embark on my doctoral journey, my father encouraged me and told me from his hospital bed while ailing to ensure that I earn my Doctorate come what, and here I have it. May his soul rest in eternal peace.

ACKNOWLEDGEMENT

This study was successful because several people gave invaluable support over the entire research period. I would like to express my gratitude to Prof. Oludolapo Akanni Olanrewaju for giving me the opportunity to undertake this study under his guidance and supervision, support, and encouragement over the whole period, and without whom, this research would not have been possible. For that reason, a wonderful experience at the Durban University of Technology in my doctoral journey, has come to an end. I learnt the challenges facing the energy transition from fossil fuel dominated energy mix to a future energy system dominated by renewable energy and low carbon energy systems, the application of new approaches like V2G (Vehicle to Grid) and G2V (grid to vehicle), conversion of traditional energy consumers to prosumers with the smartening of electricity grids and decentralisation of power generation and technological advances in energy storage and carbon capture and sequestration and planning with modern modelling tools to enhance planning for energy efficiency, optimisation of energy resource consumption and deployment of generation units for a stable, reliable and efficient power system. I wish to express my sincere gratitude to my entire family, my daughters, sons, and extended family for always motivating me over the entire period in a country far away from home, making me at home and was never lonely. This work would not have been possible without continued support from the University of Nairobi in Kenya, which granted me a study leave for four straight years from 2020 to 2023. Durban University of Technology offered all the necessary learning and research tools and financed together with my supervisor publication of research outputs in high impact journals and payment for the more than 60 conference paper presentations and publications. Therefore, I could not have accomplished the D.Eng. tenure at Durban University of Technology without the full support of my family, friends, and colleagues at the University, and above all the support system in general available courtesy of the Government and the great people of the Republic of South Africa.

ABSTRACT

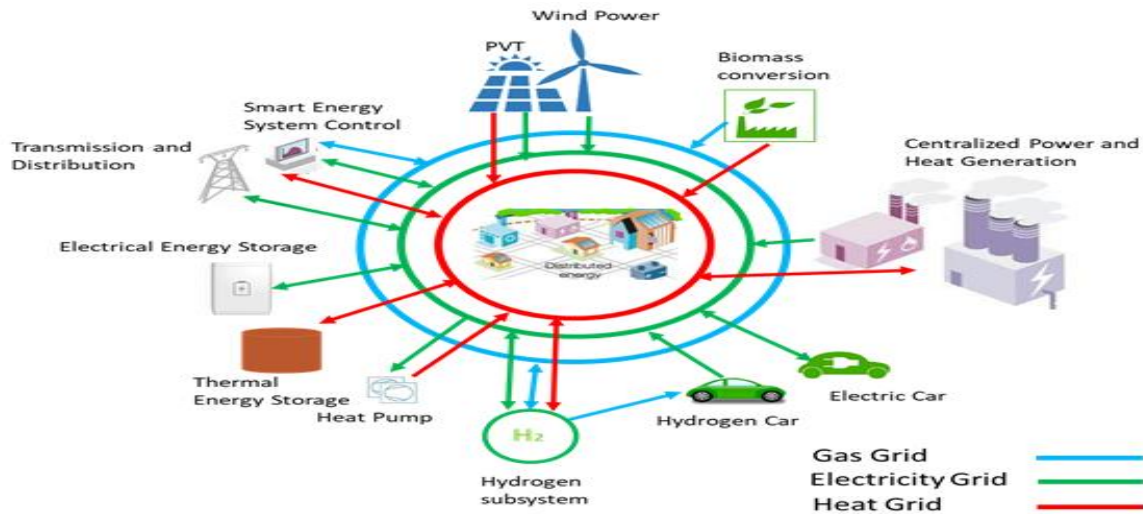
Clean and low-carbon energy sources and technologies have emerged as a critical driver in delivering the energy transition and achieving net zero-carbon emissions. All energy sources and power systems produce greenhouse gases (GHGs) and hence they contribute to anthropogenic greenhouse gas emissions and resultant climate change besides contributing to other negative environmental impacts. Energy sustainability remains a major challenge globally due to current heavy reliance on depletable and polluting fossil fuels for most of global energy needs. This study examines the energy transition strategies and proposes a roadmap for sustainable energy transition for sustainable energy planning and grid electricity generation and supply in wake of commitments made by the world community to the Paris Agreement aimed at reducing greenhouse gas emissions and limiting the rise in global average temperature to 2°C and preferably 1.5°C above the preindustrial level and realisation of the sustainable development goal of the United Nations. The sustainable transition strategies typically consist of three major technological changes namely, energy savings on the demand side, generation efficiency at production level and fossil fuel substitution by various renewable energy sources and low carbon non-renewable sources like nuclear power and carbon emission reduction strategies like carbon capture and sequestration and a conversion from high carbon fossil fuels like coal and oil to natural gas which remains the cleanest fossil fuel. The study demonstrated that decentralised generation with application of both demand side management and behind the meter management (BTM) strategies are effective measures to increase the use of renewable energy resources which are often locally available leading to higher uptake of renewable energy sources and conversion of consumers to prosumers making the transition economically sustainable. Waste to energy options have a significant potential to contribute to the energy transition e.g. use of biowaste for biogas production, slaughterhouse waste biogas production for biogas and electricity generation and waste treatment and disposal, waste heat recovery from used geothermal for extra power generation and reinjection to improve the reservoir sustainability and use of bagasse and sugarcane trash for grid-based power production in sugar factories. Therefore, domestic, and industrial scale waste to energy conversion can enhance the economic sustainability of waste management process by offering useful energy substitutes for fossil fuels and enhanced energy security through decentralisation of generation. Whereas sustainable development has social, economic, and environmental

pillars, energy sustainability is best analysed by five-dimensional approach consisting of environmental, economic, social, technical, and institutional/political sustainability to determine energy resource sustainability. The study recommends the adoption of sustainability-based planning for energy development and optimisation of electricity generation and supply where energy sources are analysed and ranked based on the five dimensions of energy sustainability instead of Least Cost Development Planning (LCDP) often applied by many countries. On this basis, the sustainable energy transition and optimisation of power generation will rely on both renewable and non-renewable energy since both have an important role in the realisation of the energy transition plans even though the desire is to shift entirely to renewable energy sources by the year 2050. The sustainability of various energy sources was assessed with hydrogen, wind, solar, sugarcane bagasse and cane trash, biogas and ocean energy technologies proving to be among the most sustainable renewable energy and sustainable sources. The study also examined various power plants and energy conversion systems for electricity generation in terms of their specific role and potential in grid-based power generation with hydro power plants, geothermal, nuclear, fuel cells, raking high on performance indicators like load and capacity factors making them ideal for base load power supply. Diesel engines and gas turbines using cogeneration and dual cycle systems powered by cleaner fuels like natural gas, hydrogen and biomethane will play an important role in supplying intermediate and peak load power. The study highlighted enabling technologies and concepts in the energy transition which include decentralisation of generation, cogeneration and trigeneration, demand side and behind the meter management microgrids and smart grid technologies, energy and generation planning and optimisation models, energy storage, electrification of transport and use of electric cars as decentralised electricity sources through the V2X technologies like the G2V and V2G, and carbon capture and sequestration for emissions reduction in fossil fuel power plants making them more sustainable. The study classifies electric vehicles as distributed power plants and variable loads with extensive use of energy storage while sugar cane bagasse is noted as a sustainable energy resource for power generation by cane sugar factories by application of more efficient grid connected cogeneration power plants. The study identified long project gestation period as the main factor limiting nuclear and geothermal energy deployment and recommends the adoption of modularised wellhead generators and small modular nuclear reactors (SMRs) as a

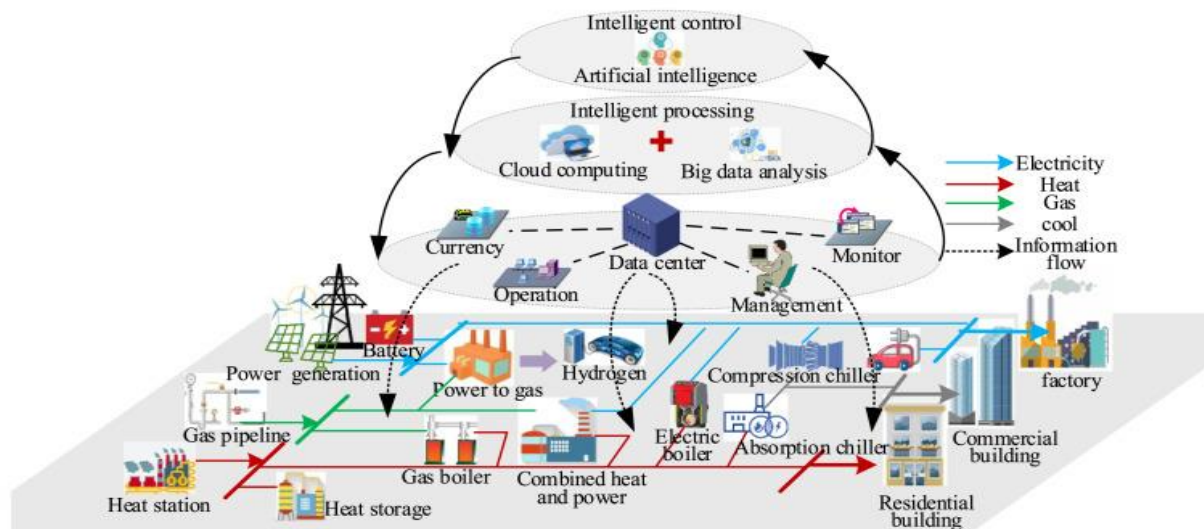
solution to enhance exploitation of these sustainable energy and technologies through faster deployment with high degree of flexibility. Biogas and biomethane demonstrated significant potential as renewable energy sources for power generation and substitute fuels in all applications of fossil natural gas. The study recommends sustainability-based planning for the energy sector and power generation and use of both renewable and non-renewable but sustainable sources of energy, adoption of smart energy concept by all sectors and investment in energy technology and infrastructure development for hydrogen and other promising energy sources like ocean thermal, wave and tidal energy and the conversion of the transition from the traditional to smart grid systems and a shift from centralised to decentralised power generation. Since the transport sector accounts for a significant portion of the global greenhouse gas emissions, electrification of the transport sector and coupling with the power sector is a key strategy recommended for the transition with the smart grid and microgrids playing an enabling role. Since energy sources and generation technologies have associated emissions occurring at different sections of the lifecycle, the use of lifecycle costs and emissions are helpful in long term energy and generation planning which demonstrate that renewable sources and nuclear are the most sustainable when analysed within the five dimensions of energy sustainability, but with the non-renewable sources playing a critical role as dispatchable sources for sustainable grid power generation, while the smart grids and use of energy storage can increase the uptake of variable renewables to as high as 95% to 100% up from a low of 20-25% uptake of variable renewables with the traditional grid. This will significantly help the world in achieving the global emissions and climate targets as stipulated in the Paris Agreement as well as the sustainable development goals (SDGs).

Graphical Abstract

The overall objective of the study was to provide solutions to build global energy systems based on renewable and sustainable energy resources and optimise power generation and consumption by use of sustainable energy resources and generation technologies based on the five dimensions of energy sustainability. A sustainable energy system should intergrade electricity and other sectors through smart electricity grids, smart gas grids and smart heat grids as demonstrated below.

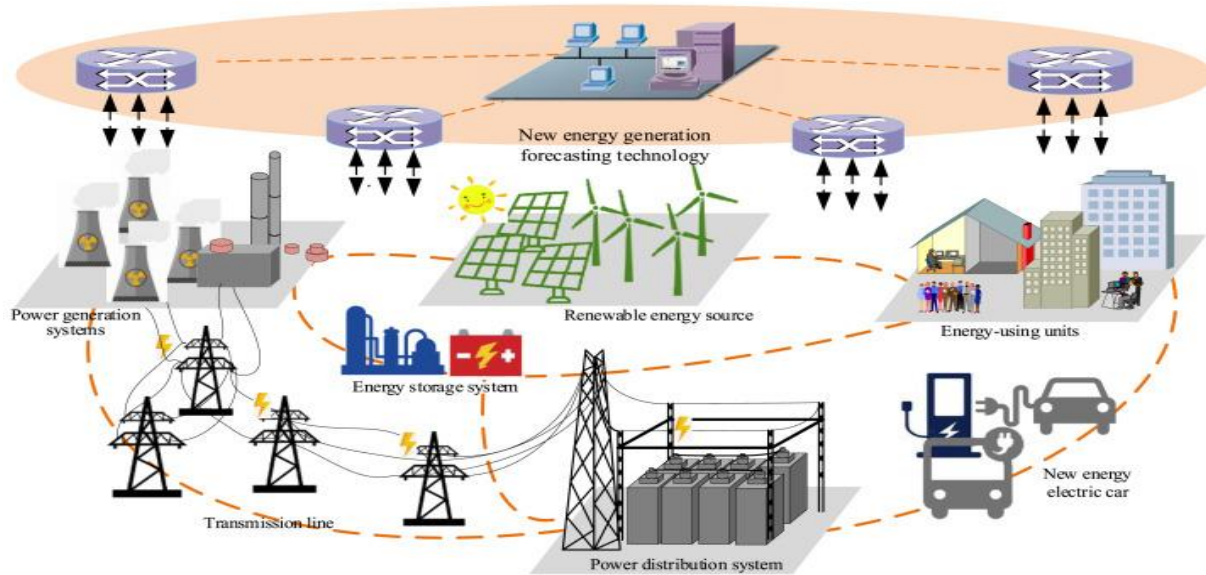


Additionally, a sustainable energy system is made of smart energy systems which incorporate incorporates a variety of key technologies and energy sources. The energy transition also requires an intelligent power generation prediction technology of smart energy systems demonstrated below.



Sustainable power generation should incorporate modern energy power generation prediction technology for maximum uptake of photovoltaics, wind energy and other variable renewables to enable hourly, minute, and second-level prediction performance, and hence plays a critical supporting role in new energy generation's safe and stable operation.

For the world to realise extensive penetration of fluctuating sources mainly wind solar and variable loads like electric cars, it is important to rethink the design of the energy system and switch to a more coherent Smart Energy System approach as demonstrated below.



Within the framework of 100% renewable energy system, the transport sector remains one of the most challenging. When viewed from the current knowledge and expectations, it is not possible to make a total shift to renewable energy and electrify all operations and hence some operations like heavy duty transport, shipping and air travel will continue to rely partially on or fully on liquid or gaseous fuels. It is also impossible to fully rely on renewable sources alone due to the fluctuating nature of the dominant renewables and the dynamic nature of electricity demand. As a solution, to this challenge, it is important to rethink the production cycle of hydrocarbons and, simultaneously create flexibility to facilitate extensive penetration of fluctuating sources of energy which are critical for the energy transition into the electric power grids. Both mature and evolving technologies are investigated with some remaining uncertain due to limited technology and infrastructure investment and progress, while others have matured, and are being deployed and need optimised measures in exploitation. The smart energy concept is identified as the best strategy to couple or integrate major energy consuming sectors of the economy and optimise energy resource use and power generation and consumption as a strategy in the energy transition to minimise related greenhouse gas emissions and mitigate climate change.

RESEARCH OUTPUTS AND KNOWLEDGE DISSIMILATION

This thesis is supported by the author's published journal Papers, book chapters, unpublished works being reviewed for publication, and conference papers presented locally and international with the author as the corresponding author and the supervisor as the co-author.

List of Journal Publications

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OPERATIONAL DEFINITION OF TERMS

Grid: A network of cables connecting power stations to consumers via the transmission and distribution networks

Traditional grid: The network connecting centralised power stations and consumers in a unidirectional flow of electricity.

Smart grid: An intelligence grid connecting power plants and electricity consumers equipped with advanced electronics and communication systems supporting two-way flow of electricity and communication.

Centralised generation: Power generation done in big power stations located far away from consumers connected via both the transmission and distribution networks.

Distributed generation: Generation done at the point of use or close to point of consumption where consumers and power producers are connected via the distribution grid.

HIGHLIGHTS OF THE RESEARCH

- All electricity generation technologies emit greenhouse gases at some point in their lifecycle and hence have a carbon footprint.
- Fossil-fuelled generation led by coal the highest contribution to global electricity generation, but have a high carbon footprint, with most emissions produced during plant operation.
- Carbon capture, storage and use could significantly reduce fossil fuel emissions reduce these significantly, though this is unproven at full scale.
- Nuclear and renewable generation generally have a low carbon footprint with most of the related emissions produced indirectly during the development and construction of the technology itself.
- Carbon footprints are sensitive to factors like the conversion technology used even for the same energy source hence the need for careful selection of power plants and conversion and operating technologies adopted.
- A sustainable mix of energy sources, conversion technologies, energy and power system infrastructure in a facilitating political and social environment is a prerequisite for sustainable electricity generation and supply and should therefore be the starting point for sustainable energy transition.
- The Paris Agreement of 2015 sets targets to be realized to limit greenhouse gas emissions and related global warming with the objective of reducing greenhouse gas emissions and global average temperature rise.
- The cumulative effect of the Stockholm, Rio, and Johannesburg conferences made sustainable energy development (SED) a very important factor in sustainable development.
- The energy transition seeks to transform the world order with respect to development and environment and particularly the use of energy in its many forms with priority to electricity.
- Sustainable energy transition should incorporate the three dimensions of sustainable development of social, environment and economic in addition to technical and political/institutional dimension.

- A sustainable global electricity transition will entail increased use of renewable energy sources particularly wind and solar, nuclear energy as a low carbon energy source, electrification of transport and thermal processes in industry, bioenergy, and waste to energy conversion, shift from coal and petroleum to natural gas, hydrogen as a fuel with low carbon footprint, increased energy efficiency.
- This transition can only take place successfully through collaboration between players locally and international with effective facilitating policy framework, facilitating infrastructure and technology development and adaptation, use of smart grids and various modelling and optimization facilities in decision support.
- Smart energy systems led by the smart grid infrastructure are identified as critical for this transition.
- Decentralized generation is considered as a solution to the realization of a sustainable electrification program by promoting use of local resources and reducing distribution losses and costs.
- Off grid energy and power solutions led by the micro grids are considered as a critical component of the sustainable energy and electricity transition
- Biogas, biomethane, and bagasse are treated as separate energy resources not just biomass due to their projected significant roles.
- Geothermal is split into conventional and wellhead power plants using different conversion technologies.
- Nuclear energy is divided into conventional nuclear power plants, modular power plants, and fusion power plants in this study.
- Hydropower is divided into hydro with storage, river flow and pumped hydro power plants which are also treated as storage technologies.
- Electric vehicles are treated as sources of decentralized power generation and grid connected storage in addition to being variable loads.
- In this study, planning and dispatch of power plants is based on their sustainability unlike the traditional approach which is based on least cost power development plan (LCPDP)
- The main dimensions of sustainability in energy development and consumption are environmental, social, political, economic, and technical sustainability.

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LIST OF ACRONYMS/ABBREVIATIONS

AC:	Alternative Current
AF	Availability Factor
BESS	Battery Energy Storage System
BTM	Behind the meter management
CBD	Compressed biogas
CHP	Combined heat and power
CI	Carbon intensity
CSP	Concentrated Solar Power
DC	Direct current
DFIG	Double Fed Induction Generator
DG	Decentralised generation
DNO	Distribution Network Operator
DSM	Demand side management
EHV	Extra High Voltage
EMF	Electromotive force
HRT	Hydraulic retention time
IEEE	Institution of Electrical and Electronic Engineers
IRP	Integrated Resource Plan
KES	Kenya shillings
LBG	Liquid biogas (LBG)
LDC	Line drop compensator.
LHV	Lower heat value
LPU	Large Power User

MHD	Magnetohydrodynamics
NA	Not applicable
NZE	Net zero emissions
OTEC	Ocean Thermal Energy Conversion
PTC	Production tax credit
PV	Photo Voltaic
RES	Renewable energy sources
RGE	Renewable green energy
SA	South Africa
SCIG	Squirrel Cage Induction Generator
SD	Sustainable development
SDP	Spatial Development Plan
SED	Sustainable energy development
SG	Smart grid
SMR	Small modular reactors
SPU	Small Power User
SRT	Solids retention times
SSEG	Small Scale Embedded Generation
TEI	Transport energy intensity
TPES	Total primary energy sources
VRES	Variable renewable sources of energy
WACC	Weighted average cost of capital.
WRIG	Wound Rotor Induction Generator
WTG	Wind Turbine Generator

CHAPTER 1:

INTRODUCTION

1. Overview

This chapter presents an introduction to energy sustainability and energy transitions and the global status of electricity generation and impacts. The chapter provides a general introduction to energy and power systems, the main environmental challenges posed by the current system, and the underlying rationale for long-term modelling of the anticipated energy transition. The aim and objectives of the research are then presented, followed by a discussion of some of the limitations of this work. The contents of this chapter are supported by the author's publications[1-3].

1.1 Background

The 2021 United Nations Climate Change Conference (UNFCCC), also known as COP26, demonstrated the urgent need for accelerated action towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change. Climate change is taking place at an alarming rate, mainly due to human activities that release greenhouse gases (GHGs) into the atmosphere[4]. About three-quarters of greenhouse gas emissions today come from the energy sector making it key in averting the worst effects of the climate change. The need to reduce global carbon dioxide (CO₂) emissions to net zero by 2050 is key to limiting the long-term increase in average global temperatures to 2°C and preferably 1.5°C above the preindustrial temperature level as stipulated in the Paris Agreement of 2015. This calls for a total overhaul and transformation of production, transportation, and consumption of available energy resources. Significant input is needed to convert existing emissions and climate ambitions into reality because of many existing limitations and opportunities that different countries encounter in meeting their climate and emissions targets [4, 5]. The Paris Agreement of the year 2015 established long-term goals for governance of the global climate change, meant to limit the global temperature rise to below 2 °C, and more preferably to 1.5 °C[6]. There is a need for transition to a low-carbon energy and electricity sector to tackle the global challenge of climate change. Integrated application of multiple low carbon technologies is a requirement for emissions reduction in the power sector. The various power generation technologies

include wind, nuclear, solar, nuclear, biomass and other renewable energy generation technologies; carbon capture, energy storage and utilisation technologies; and biomass coupled carbon capture technologies and a transition from the traditional grid to smart grids and smart micro grids[6, 7].

Natural increases in CO₂ concentrations have historically been warming the earth during ice age cycles for millions of years. Warm episodes are said to have started with a slight increase in solar radiation reaching the earth due to a slight wobble in Earth's axis and path of rotation around the Sun that caused some little warming. This phenomenon caused the warming of oceans leading to an increase in carbon dioxide (CO₂) from the oceans causing an increase in rate of global warming. However, CO₂ concentration never exceeded 300 ppm during these periods of about a million years ago. Before the industrial revolution that started in of mid-1700s, the global average amount of carbon dioxide was about 280 ppm [1, 3, 8]. Figure 1-1 shows the historical growth of CO₂ emissions and concentration between 1751 and 2022.

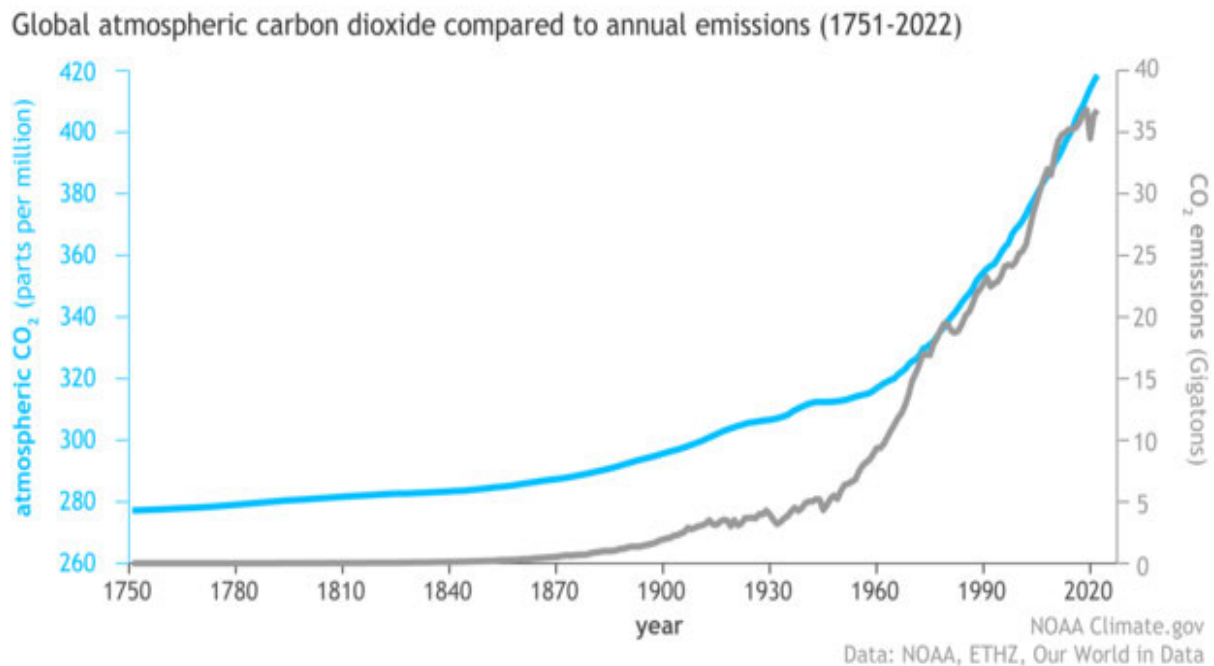


Figure 1-1: Concentration of Carbon Dioxide Emissions between the year 1750 and 2022 [9, 10]

From Figure 1-1, it is observed that the global CO₂ emissions remained constant between 1751 and about 1840 when they started increasing. The atmospheric concentration increased slightly between 1751 and 1960 where the rate increased significantly to the year 2022 mainly due to

increased use of fossil fuels and growth in industrial activity. Therefore, it is the entry of fossil fuels into the energy mix that triggered rapid increase in CO₂ emissions as the level of industrialization developed.

There is a need for a global transition in electricity generation, transmission and distribution and consumption to achieve the global emissions and climate targets. Humanity must strike a balance between developmental needs and environmental conservation and protection. The main challenges facing renewable energy sources is resource availability, resource access, resource location, security of supply, sustainability, and affordability [11, 12]. The growing demand for electricity has led to increased demand and consumption of fossil fuels and growing level of economic activities have contributed to growth of the greenhouse gas emissions and consequently, global warming[13].

The world continues to experience the impacts of climate change making it clear that greenhouse gas emissions must fall. However, according to the Emissions Gap Report (EGR) 2022, the international community has fallen far short of the Paris goals, with no credible pathway to 1.5°C target in place hence the need for urgent system-wide transformation to avoid the climate disaster[14]. The report shows that the national pledges since COP26 – held in 2021 in Glasgow, UK, have made negligible difference to predicted 2030 emissions and the Paris Agreement goal of limiting global warming to below 2°C and preferably 1.5°C is far from being achievable with current policies pointing to a 2.8°C temperature rise by the end of the century. Existing conditional and unconditional pledges will only reduce the temperature rise to between 2.4-2.6°C by the end of the century. Therefore an urgent system-wide transformation is needed to limit greenhouse gas emissions and avoid the climate disaster [14]

The exploitation of all energy sources and power systems produces greenhouse gases (GHGs) and hence they contribute to anthropogenic climate change besides contributing to other negative environmental impacts. Energy sustainability or also referred to as energy for sustainable development remains a major challenge globally. The current heavy reliance on depletable energy sources mainly in the form of fossil fuels is not sustainable in the long term and this will compromise the ability of the future generations to meet their energy needs while at the same time significantly contribute to global climate change. It is imperative to have a

clear idea of energy sustainability for policy and planning purposes since energy is an essential input for almost all economic activities and human well-being in all nations affective all humanity[15, 16].

Rapid decarburizing of the grid electricity and therefore the society at large ideally requires maximum use of renewable sources[17]. However large scale renewable integration can lead to undesirable system conditions like loss of synchronism, load shedding, voltage collapse, large frequency and voltage deviations, introduction of flicker and harmonics, high system losses, over loading and increased power oscillation[17, 18]. Wind and solar photovoltaics are increasingly becoming cost competitive and environmentally friendly, but remain highly variable and unpredictable in terms of availability, output and capacity[19]. This implies that for optimum operations, the system needs high level of dispatch able power plants to supply electricity during times of low availability of the renewables[19]. Although it appears like the world should shift from fossil fuel dominated electricity to 100% renewable energy to save the environment, protect economies and save the world from oil and energy wars, there is technological capability to use fossil fuels and other non-renewable sources like nuclear energy with little or no harmful emissions and other pollutants and clean coal and fossil fuel technologies. Additionally, fossil fuels like coal will remain abundant and cheap for many years to come, hence a guarantee of cheap or affordable energy and power[20]. Sustainability requires that electricity generation and supply should meet the triple requirements of economic, social, and environmental sustainability. These requirements cannot be met by renewables alone, but an optimised mix of all feasible energy sources in an optimized manner [21].

There is a need for energy in form of electricity to meet the ever-growing needs of mankind. A sustainable electricity mix should satisfy the economic, social, and environmental dimensions in a facilitating political environment. Energy supply for global sustainable development should be based on safe, clean, low carbon and renewable forms of energy[22]. A sustainable electricity mix will use technology and infrastructure like smart grids, and measures like energy conservation and efficiency solutions, decentralized generation, cogeneration, and electrification of transport. Use of computers programs and hardware to manage generation resources can help in optimization of the energy mix for sustainable power generation and supply. A mixture of options is necessary to lower the unit cost and carbon intensity of

electricity systems. The objective of this study is to realise sustainable electricity that is economical, quality and environmental friendly produced in a manner that will help nations realise the Paris protocol and the Paris agreement of 2015[21, 23]. Although the most desirable scenario is where all electricity is generated from renewable sources, the need for the three dimensions of electricity call for an optimized mix of energy sources that are renewable, low carbon and non-renewable. The study seeks to maximize the use of renewable and low carbon sources by application of facilitating technologies like storage, smart grid technologies, and electrification of transport with application of vehicle to grid (V2G) and grid to vehicle G2V interface technology.

It became obvious and clear after the Paris Agreement of the year 2015, that all countries must undertake fast and substantial energy transition to reduce greenhouse gas emissions and the unsustainable use non-renewable natural resources particularly the fossil fuels. Power generation should shift from a centralized configuration based on fossil fuels to a more distributed system based on renewable energy resources (RES) like solar and wind which are variable in addition to low carbon non-renewable sources like nuclear power. This calls for new products and services for maximum use of variable renewable sources of energy (VRES) for accurate and reliable production forecast, improved dispatchability, by efficient use of storage systems, higher system reliability, and active participation to the electricity market to ensure that energy transition delivers benefits to the environment and the society as a whole [5].

Decarbonisation of the energy sector is an urgent global scale action, with more action needed to reduce carbon emissions and mitigate the effects of global climate change. Among other measures, the use of renewable energy and energy efficiency measures can realise as high as 90% of carbon emission reductions[24]. A sustainable energy transition will be facilitated by advances and application of information technology, use of smart technology, facilitating legal and policy frameworks and energy/electricity market instruments. Therefore, energy transition represents a profound change in electricity and the entire energy sector. Energy transition requires major changes in energy supply, energy production or processing, energy conversion, electricity and heat delivery, and consumption in a wide variety of energy markets and policies. Energy transition has far reaching implications and effects well beyond the energy

system itself, like transformation of many parts of the economy, society, and environment which are the key dimensions of sustainable development[24, 25].

Energy sustainability or more formally energy for sustainable development remains a major challenge for all countries, both developed and developing countries because energy is an essential input for all economic activities and human well-being hence making it necessary for countries to develop and sustain humanity[15]. Globally, energy is playing a critical role in the modern life of all countries hence the need to understand how sustainable energy supply and consumption system is and how to attain and maintain energy sustainability[15].

There is need to scale up renewable energy uptake by at least six times faster if the world is to meet the decarbonisation and climate mitigation goals set by the Paris Agreement. For this to happen safe, widely available, and reliable technologies are needed. There are many different paths to achieve the climate and emissions targets with use of renewables and energy efficiency leading among the paths. The current actual carbon dioxide (CO₂) emission trends are off track, and the world may exhaust its energy-related carbon budget in less than 20 years. Additionally, fossil fuels will continue to dominate the global energy mix for decades to come. The share of renewables need to increase from the current level of about 15% of total primary energy sources (TPES) in 2015 to about 66% in 2050[26].

There are different pathways for mitigating climate change, but energy efficiency and renewable energy use can deliver most of the emission reductions needed at necessary speed and can jointly provide over 90% of the energy-related CO₂ emission cuts by application of affordable, safe reliable and widely available technologies. Renewables can make up 60% or more of the final energy needs of many globally[27].

The understanding of socioeconomic footprint of the energy sources for the energy transition is essential to facilitate optimisation of solutions. The energy transition should be analysed within the socioeconomic system in which it is deployed. This implies that different countries should pursue different transition pathways and different transitions unique to socio-economic systems. The socioeconomic benefits of energy transition should go well beyond the gross domestic product (GDP) improvements, to include marked social and environmental benefits. At country and regional level, the energy transition should be guided by national and regional ambitions as well as socioeconomic structures and prevailing circumstances including

employment levels and concerns [2, 27]. With adequate policies, the energy transition can greatly enhance the overall employment in the energy sector. Renewables will create more jobs in the energy sector compared to those lost in the fossil fuel industry [3, 23, 28]. A good transition should generate fair and just socioeconomic outcomes that do not cause resistances that can halt it [2, 3, 29].

The world should immediately accelerate the energy transition today preferably based on renewable energy and energy efficiency, to avoid accumulation of energy assets, which may end up being stranded; reduce negative environmental impact and health damage from fossil fuels; and minimise the need investment in expensive and largely questionable technologies, like carbon capture and storage as well as risky nuclear power [30]. Energy financial products should align themselves with sustainability and energy transition needs and features since financial constraints and inertia can limit investment needed to deliver the desired energy transition. Other benefits from increased access and reduced cost of borrowing can increase both GDP and employment while at the same time enabling the sustainable energy transition pathways [27, 31]. Governments should introduce policy measures and structural socioeconomic modifications that increase availability capital without compromising the stability of local financial markets. Finance sources that do not contribute to sustainable energy investment need to be unlocked. The potential sources of finance for the energy transition investment include institutional investors like pension funds, endowments, insurance companies, sovereign wealth funds and local community-based finances. Rapid actions should be taken to remove any potentially significant barrier to the energy transition and facilitate faster deployment of clean and modern energy technologies [27, 29].

1.2 Problem Statement

The global greenhouse gas emissions continue to rise after a slow down caused by COVID-19 that led to a reduction of 4% in CO₂ levels between 2019 and 2020. The level rose to reach a new high of 415.7 ppm in 2021 and reached 417.06 ppm in the year 2022. The UN reports indicate that to meet the 1.5°C target, the trend must be reversed to bring about a 43% reduction in greenhouse gas emissions by 2030 and to net zero by 2050. Unfortunately, current national commitments are not adequate to meet this goal, with fossil fuels still

accounting for about 90% of global CO₂ and 75% of all greenhouse gas emissions making fossil fuels the the largest contributors to climate change.

Humanity has increased the concentration of carbon dioxide in our atmosphere, thus increasing the Earth's natural greenhouse effect which is still ongoing and remains a continuous threat to the global environment. The annual rate of global increase in atmospheric CO₂ over the last sixty years is close to 100 times faster than natural increases like those that occurred the end of the last ice age about 11,000-17,000 years ago. The composition reached 409.8 ppm in 2019. The ocean pH has been lowered by 0.1 from 8.21 to 8.10 since the beginning of the industrial revolution representing a 30% increase in acidity of the ocean. These is undesirable because of the biological effect of ocean acidification like interference with ability to extract calcium from the water to build the shells and skeletons of marine life[3].

The energy sector is the largest contributor of global carbon dioxide emissions and second largest contributor of non-carbon dioxide greenhouse gas emissions globally. With electricity being the leading source of greenhouse gases, any effort to minimize greenhouse gases should address emissions from the power sector. Sustainable grid electricity requires facilitating technologies and infrastructure like smart grids, and concepts like decentralization of generation and demand side management. A mixture of options is necessary to lower the unit cost and carbon intensity of energy systems to achieve truly sustainable energy. Energy related GHG emissions are a result from conversion and delivery sectors like extraction/refining, power generation and direct transport of energy carriers in pipelines, cables, ships, tracks an end use sectors and industries like transport, buildings and construction, manufacturing, agriculture, forestry, households, and waste and hence cannot be blamed entirely on one sector or process alone[3, 32].

Energy storage has an important role to play in the transition to low carbon future especially through enhanced use of intermittent renewable energy sources. The main dimensions of sustainability are economic, social, and ecological and the facilitating political environment. The conversion of the traditional or conventional grid to a smatter power grid will maximize the use of variable renewable sources of energy like solar, wind, mini and small hydro's as well as small farm level biogas plants for grid electricity generation[3, 16].

The Intergovernmental panel on climate change (IPCC) predicted that a greenhouse gas emission (GHG) will lead to global temperature increase of between 1.1 - 6.4°C by the end of the 21st Century, and that the world would experience about 62% increase in CO₂ emissions between 2011 and 2050 if energy demand and use of fossil fuels to meet the demand does not change. To maintain ecological sustainability, organizations should consume natural resources whose consumption rates are lower than the rate of natural replenishment or reproduction. Where substitutes exist, the rate of consumption is lower than the rate of substitute development. Greenhouse gas emissions should be reduced by between 50-80% by the year 2050 if the world must avoid the looming consequences of global warming[23, 29].

The composition of atmospheric carbon dioxide (CO₂) has been rising as summarized in Table 1-1.

Table 1-1: Increase in CO₂ concentration between 1750 and 2022[3].

	Year	Concentration (Ppm)	Percentage (%)	Year To Year Increase (%)
1	1750	277	Reference year	Reference year
2	2014	397	43.33	43.33
3	2015	400	44.40	1.07%
4	2018	407.4	46.93	2.53 (for 3 years)
5	2019	409.8	47.94	1.01
6	2020	412.5	48.92	0.98
7	2021	415.7	50.07	1.15
8	2022	417.06	50.56	0.49

Table 1-1 shows that between 1750 and 2022, the atmospheric concentration of carbon dioxide has increased from 277 ppm to 50.56 ppm representing an increase of 50.56%.

Figure 1-2 shows the increases in the concentration of CO₂ emissions between 1750 and 2022.

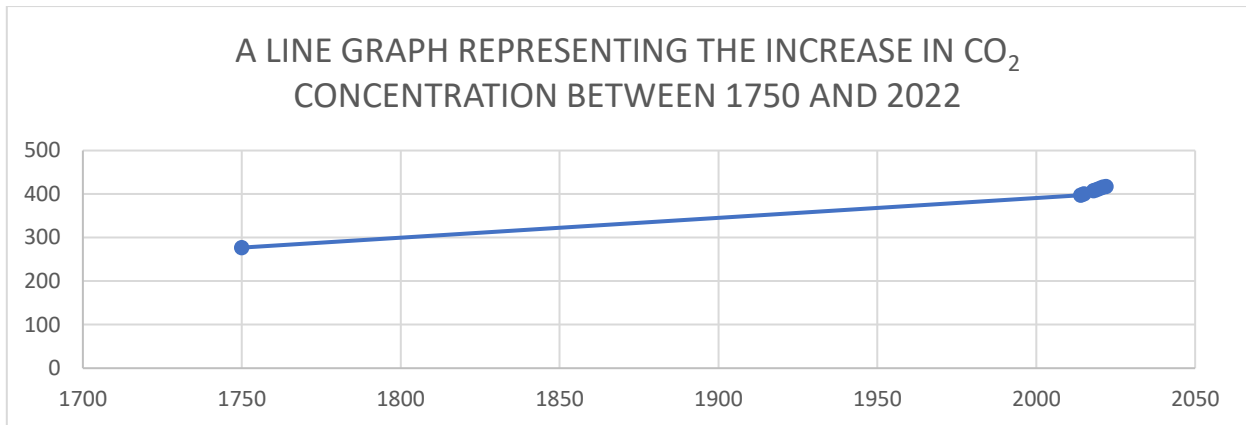


Figure 1-2: Increase in CO₂ concentration between the year 1750 and 2022.

For a stable atmosphere, the global average temperature increase should be maintained between 1.5 and 2°C above the preindustrial level which translates to atmospheric carbon dioxide concentration of 400 to 450 ppm. Energy resources are sources of various past and current political and social conflicts and therefore it is through proper energy resource management that many social, political, and economic conflicts can be avoided or resolved globally. Countries can use renewable energy sources like solar, wind and even hydro to enhance their national energy security because these resources do not need international trade to secure them and hence cushions countries against energy instigated insecurity. Governments should play a proactive role in the transformation but should non-state actors to nature the transformation to green and low carbon electricity[3, 32, 33].

Global Industry and buildings are the main users of electricity accounting for over 90% of global electricity demand as transport accounts for less than 2%. Moving forward, the main drivers of electricity demand growth are motors in industry which may account for over 30% of the total growth to 2040, industrial and domestic space cooling will account for 17% while large electrical appliances are projected to account for 10% growth and electric vehicles are projected to account for 10% growth in electricity demand. A further growth in electricity demand of about 2% is projected to come from the provision of electricity access to 530 million first-time users of electricity. The sustainable development scenario, projects that electric vehicles will become a leading source of electricity demand moving to the future towards the year 2040. Therefore, a sustainable electricity transition should prepare for wider use of variable renewables, low carbon nuclear power, electrification of transportation, better

and efficient conversion, and efficient energy use technologies and electrification of thermal application of energy particularly in the industry[3, 34, 35].

The Parties to the 2015 Paris Agreement made a commitment to limit global warming to well below 2 °C and then to pursue efforts to limit the rise to 1.5 °C relative to pre-industrial times. Unfortunately, fossil fuels continue to dominate the energy mix accounting for close to 81 % of primary energy consumption [36]. As per the gap report on emissions, the world is not on track to reach the Paris Agreement goals and global temperatures targets since the temperature may reach 2.8°C by the end of the century. To remain on track, the world should reduce emissions by 45% to prevent global environmental catastrophe [14].

The growing global population, urbanization, and industrialization have significantly increased the demand for energy and natural resources. The world's population has so far increased by close to 2.5 times since 1950, while energy demand has grown by close to 7 times which demonstrates the rapid growth in energy demand by the growing population [3, 37]. The related energy challenges include diminishing fossil fuel reserves, fuel price volatility and, and global climate change which have generated growing interest in sustainable and renewable energy sources[16, 37]. This has led many countries to put in place institutional and policy measures to support the energy transition from fossil fuels to sustainable energy and renewable sources of energy hence increased search for clean and sustainable energy options for power generation, transmission , distribution and consumption [38, 39]. The world is currently facing a climate emergency with global greenhouse gas emissions not anywhere close to what is needed to avoid massive consequences of global climate change. The emissions from commissioned and operating power plants alone have exhausted the carbon budget compatible with limiting global warming to 1.5 degrees[40]. This calls for largescale, rapid, and sustained greenhouse gas emissions reductions to avoid the looming global crisis resulting from global climate change. Massive emissions reduction should be undertaken in all sectors especially heavy polluters like transport, agriculture, and power generation. Since power generation alone accounts for over 40% of total emissions, availability of low carbon energy substitutes and other emission reduction measures will make a significant global impact [2, 41].

Whereas the costs of Solar PV and wind have been reducing, they are highly variable and unpredictable which is a real challenge for a secure and reliable electric power system operation and maintenance. The deployment of these variable and intermittent needs highly dispatchable generation capacity on standby which is conventionally supplied by fossil fuels whose supply is often affected by interruptions from plant failures, fuel supply interruptions, droughts, and price fluctuations[42]. Electricity systems are witnessing a profound transformation, with a greater role for smarter grids going hand in hand with increased solar and wind deployment. Electricity transmission and distribution systems provide the bedrock of today's and tomorrow's power systems, enabling electricity to flow and all sources of flexibility to contribute to electricity security. Therefore grid expansion must accelerate to connect all new sources of electricity, including renewables, extending grids by 16 million kilometres, 80% more than over the past decade [43].

The emission of greenhouse gases (GHGs) and their implications to climate change have sparked a global interest in understanding the relative contribution of the electrical generation industry. According to the Intergovernmental Panel on Climate Change (IPCC), the world emits approximately 27 giga tonnes of CO₂e from multiple sources, with electricity production emitting 10 giga-tonnes, or approximately 37% of global emissions[1, 12, 44]. In addition, electricity demand is expected to increase by 43% over the next 20 years. This substantial increase will require the construction of many new power generating facilities which provides opportunities for development of less polluting and socially acceptable power plans and conversion technologies [21, 45].

The global community agreed during the Paris conference of 2015 to keep the global temperature at a maximum of 2°C above the preindustrial level ([46]. The emission of greenhouse gases with carbon dioxide (CO₂) being the most dominant are directly responsible for global warming [47]. Carbon dioxide from fossil based combustion mainly in power plants is a significant contributor of the greenhouse gas emissions accounting for about 80% growth of emissions [48, 49]. This calls for maximum integration of renewable and low carbon sources which comes with significant challenges to the electricity grid. Large scale integration of renewables can lead to loss of synchronism, collapse of voltage, load shedding and significant deviation of system voltage and frequency which then leads to flicker, harmonics, high transmission and distribution losses, overloads and power oscillations which

is highly undesirable and unsustainable [50]. Simultaneous reactive power management of transmission and distribution grid can maximize the renewable penetration at all layers of the grid[3].

The climate has been changing and consequences are being felt globally. Many developing countries including South Africa are facing the three challenges of grid electricity namely cost, quality & reliability and environmental impact. The Paris Agreement set targets for all countries to reduce carbon emissions [48, 51]. Most of the greenhouse gases come from power plants of which 60% of global electricity comes from fossil fuel-based sources, led by coal and natural gas. Renewable sources like solar and wind which are significant face the challenge of intermittence and hence are unpredictable and unreliable have a significant potential to play a leading role as power sources for the energy transition, amid the challenges related to intermittence and variability. We must therefore use them as well as other renewables and low carbon sources to mitigate against carbon emissions and global warming while not compromising the cost, security, and quality of grid electricity[2, 52].

Electricity is an important form of energy end-use application which is a critical input for socio-economic growth and development. Unfortunately, power consumption is a leading source of greenhouse gas emissions and related global warming, and climate change since electricity supply is dominated by fossil fuels sources in many countries. It is therefore important to reverse the trend through increasing the share of renewable energy sources, most of which are variable [16, 53]. The energy sector vital in the global effort to tackle climate change as it accounts for about two thirds of global carbon dioxide emissions[54], yet energy particularly in form of electricity and heat drive the prosperity of the global[1]. Therefore, for the economy to grow, energy consumption must also increase. As a demonstration, from the 1970s, the global gross domestic product (GDP) has grown by about 4.5 times, while primary energy consumption has grown from 155.22 EJ in 1965 to 556.63 EJ in the year 2020 representing about 3.4 times. By the end of 2020 the proved reserves for oil will last for 48.8 years, natural gas will last for 53.5 years while coal is estimated to last for the next 139 years[55]. This is evidence that humans must develop new energy resources, new energy technologies and efficiently exploit the available resources.

Many countries are facing energy transformation and sustainability challenges which among others include broad supply–demand gap for electricity and other energy resources, extensive dependence on fossil fuels and low access and penetration of clean energy[44, 56-59]. By operating the conventional grid, the electricity utility providers have little, and at times no insight of electricity consumption by user because within the traditional grid, the operation by the utilities is purely based on prevailing demand, and in case of demand increase, the utility operators simply send more power to the grid with no other options [60, 61]. The world has witnessed significant advances in technology like the development of better electricity carriers, variable electricity pricing, advances in energy storage technologies, decentralization of generation and increased contribution of variable renewable sources energy to grid electricity, and electrification of transport which introduces variable and unpredictable loads which are challenging for the traditional electricity grid[3, 61, 62]. The main challenges facing the energy transition include how to modernize the grid, innovate, adopt new technologies, develop tomorrow's solutions, and serve local and territorial communities[12, 63, 64]. There is a need to modernize the electricity system to cope with the energy challenges and address the limitations of the traditional grid. The integration of new information and communication technologies into the grid makes it communicative enabling diverse grid actors' involvement in the electricity system, while at the same time facilitate a more efficient, economical, and safe electricity system[61, 63]. Upgrading of the electricity grid is necessary to realize energy saving schemes which empower users and support and environmental conservation[65].

There is growing demand for sustainable solutions to the electricity related environmental pollution, high power system losses, high contribution of fossil fuel sources to grid electricity energy mix which is characteristic of traditional grid systems and hence the need to increase the share of variable renewable energy sources like photovoltaics and wind, use of fuel cells, growing need to integrate storage systems and use of plug-in electric cars as pathways to sustainable energy transition[66-68]. The world community is increasingly concerned about the looming consequences of greenhouse gas emissions, most of which are related to power generation and fossil fuel based transportation [69]. With the ever-growing global electricity demand, the multiple effect is increase in cost of energy, diminishing fossil fuel reserves and hence more demand for the widely available variable renewable energy sources like wind and

solar[70]. As a move to address the challenge of global warming and limit the temperature rise to less than 2° C. as stated in the Paris Climate Agreement of 2015, the global share of renewable energy in power generation should be increased to 85% in 2050 from 33.3% in 2018[71]. This is only practical if measures are put in place to make the significant challenges that will be associated with the huge share of renewable sources, most of which are characterized by some degree of intermittent and unpredictability.

The energy sector is necessary for development and growth of the economies of all countries [72, 73]. The continuous growth of world economy and population contribute to the ever-increasing energy demand hence continued and increasing use of fossil fuels like coal, oil, and natural gas whose use is associated greenhouse gas emissions, energy insecurity, depletion of fossil fuels reserves, geopolitical, social, and political conflicts over resources and increased price and supply instability[21, 74]. These scenarios have created unsustainable situations and threats to mankind and his environment [3, 75]. As a solution renewable energy resources should be used as substitutes for fossil fuels but total replacement may not be feasible in the near future, hence the need for optimum mixing of energy sources and modernization of the electricity grid to realize this objective [29, 76]. Electrification of industrial, domestic energy applications and transport sector are also seen as major pathways in the sustainable energy transition which call for smarter grids for more efficient and effective control of electricity as an energy carrier. There is a need for self-regulation and self-reconfiguration of electric power systems by equipping power systems with the relevant intelligence and technical capabilities to improve performance, quality, and efficiency of electric power systems[3, 74].

Many electricity systems around the globe are transiting from the centrally controlled conventional grids to modern grids whose operation is influenced and controlled by the market dynamics for investment decisions, operational stability and reliability of power generation and supply [77]. The energy transition from non-renewable to renewable sources continues to face significant technical and non-technical barriers. Which may vary from one country to another and from one energy resource to another depending on the level of technology required, environmental impacts, and policy initiatives put in place by different countries [12, 78]. The challenges include poor governance, technical limitations, high energy cost, energy affordability and organizational or community resistance to change [75, 79]. The main challenges in the sustainable transition to a sustainable grid is limited access to reliable,

affordable and adequate renewable and continued reliance of fossil fuels in power generation and other energy applications like transport [80] and hence the need to shift to renewable low carbon sources of energy for grid electricity generation[3, 21].

In the view of these challenges to development and consumption of renewable energy resources for electricity generation, the use of technology can go a long way in optimizing of renewable energy penetration to the electricity grid [78, 81, 82]. This brings to focus the need for smart grids for sustainable use of both renewable and non-renewable energy for grid electricity in an optimized interconnected system [21]. Sustainable development requires social, environmental, and economical perspective, for development activities. This study explores the role of smart grids as opposed to the traditional grid to achieve sustainability and sustainable use of energy resources for electricity generation and supply to guarantee energy security, socioeconomic development, mitigation against climate change and protection of the environment while remaining economically competitive and how smart grids can be used to realize sustainability [3, 21, 74].

1.2.1 Challenges of Modern Power Systems

Traditional or conventional electricity systems consist of large interconnected networks having central power stations, transmission and distribution grids[83]. The main challenge facing power systems is to manage the system security, reliability, quality, stability and ensuring economic operation of the power systems. There are five types of system operating state, namely, normal, alert, emergency, extreme emergence, and restoration. When a power system is operating in a steady state, then it is said to be operating in normal state. This happens when generating capacity is sufficient to meet the available load demand while frequency is kept stable at 50 HZ or 60 HZ at predetermined voltage[68, 83, 84]. A normal system also has reactive power balance between generation and load demand as shown by a flat voltage profile having normal voltage throughout the system[85].

In alert state, the system reacts to a disturbance but violates a system constraint which needs preventive action to restore. Emergency is caused by a contingency like outage of a power plant, short circuit, or tripping of a power line. Whenever emergency measures fail to return system to alert or normal, it moves from emergency to extreme emergency. The system can move to restorative state by the resynchronized actions and techniques, while further

corrective actions will move it to a new normal or previous normal state. The increasing share of variable renewables, particularly wind and solar induces significant stability challenge to variable and often unpredictable nature of the energy availability and hence supply, which calls for high degree of flexibility and resilience [2, 16, 61].

1.2.2 Specific Threats and Limitations of Power Systems

The main challenge with power generation is predicting demand and selection of the best fit mix of power plants and energy sources to supply electricity demand. The challenge with load profiles and load curves is that complete profiles are often measured by utilities for their own internal use in planning and dispatch [86, 87].

Since the electricity demand and supply is ever changing, it places extreme pressure on the grid to balance generation and consumption. As a result of ever-increasing demand and increased electrification of transport and other operations, more generation and more electricity storage [88]. The main challenges facing the power grids include.

1.2.2.1 Growing Amount of Renewable Energy Sources

By 2050, it is expected that the 62 % of electricity generated will come from renewable sources of energy compared to about 27 % of the worldwide generation in 2019. Renewable energy sources are unstable energy sources and their operation can cause serious grid imbalances unless advanced management and control systems are used [16, 88]. As the share of renewables grows storage is increasingly becoming an important component of energy systems. Batteries or other energy storage systems are used to store unused energy and for future use. The use of artificial intelligence in the power systems will improve prediction systems and enable more accurate weather and energy consumption forecasts and planning by utility companies and their clients [88].

1.2.2.2 Electricity Transmission and Distribution Losses

By transmitting and distributing electricity over long distances, the losses which must be paid for by the end-users increase. The average losses are about 4-5% in Europe and much more in many developing countries e.g. 19% in India and about 50 % in Haiti [88]. A shift from big, centralised power plants to small, decentralised power plants near consumers will significantly

reduce transmission and distribution losses of power and convert consumers to prosumers [88, 89].

1.2.2.3 Frequent Power Outages

Power outages are mainly caused by extreme weather conditions and time-worn power lines. This affects millions of people and damages infrastructure worth billions of dollars. Blackouts heavily affect manufacturing and damage products like electronic devices and important data loss[88]. Power loss is a challenge to many grids and effort must be made to minimise losses and reduce recovery time. The use of smart grids with intelligence and self-healing capabilities promise to significantly reduce the challenge of frequent power loss and enhance energy self-sufficiency, while incorporation of backup sources, like storage batteries, offers long-lasting protection against power outages and hence facilitate continuous operation of at least, crucial equipment while reducing downtime in case of failure[88, 90]

1.2.2.4 Electro Mobility

Charging millions of Electric vehicles (EV) consumes significant amount of electricity, with the superchargers consuming immense amount of electricity which can cause instant change in power demand causing a stability challenges to the grid[61, 88]. Smart grids facilitate online connection of various sources like solar panels, storage batteries, electric vehicles chargers or other equipment[35]. Smart grids also enable the analysis of collected "Big data" in real-time, which speeds up the reaction time to the changes in the power grid and facilitating high quality and stable power supply [61, 88].

1.2.2.5 Grid Modernization

The traditional grid has the challenge of handling increasing share of variable renewables. The transformation from the traditional grid to the smart grid is a new dawn being undertaken by several [61, 88]. Decentralization is a leading approach in grid modernization to reduce transmission and distribution losses. Decentralisation of generation enables local power generation and use which lowers electricity distribution requirements and associated losses. This reduction in the burden on power systems enables power lines to last longer while at the same time reducing costs[1, 88].

1.2.2.6 Threat of Cyber Attacks

Digitalisation of the energy sector has been associated with cases of hackers infiltrating systems of power companies which exposes thousands of households to a controlled blackout[88]. Decentralization shifts the responsibility for the grid operation to multiple suppliers with distributed databases hence any attack on one single point in the grid, like a power plant cannot interfere with the operation of the entire power system[61, 88]

1.2.2.7 Threat of Terrorist Attacks

The danger of terrorist attack is real leading to real damage to the physical infrastructure of the power systems like transformers and power lines [88]. On the technical solution to the challenge of terrorism is use of micro grids to enable, self-sufficiency energy by communities. This makes it difficult for a terrorist group to stop the largescale power supply and will have to destroy a large number of micro grids for a huge impact[12, 88].

1.3 Aim and Objectives

This study contributes to the transformation of global energy systems and power generation and supply in a way that enable the realisation sustainable development goals e.g. SDG7 and the implementation of the Paris Agreement that seeks to reduce global greenhouse gas emissions and limit the average global temperature rise to 2 °C and preferably 1.5 °C above the pre-industrial level.

This research aims at providing information for development of a long-term as well short-term measures to achieve optimised energy mixes to guarantee minimal environmental damage, secure the power grid with affordable grid electricity. This will significantly contribute to the realisation of climate and emissions targets set by the Paris Agreement and UN sustainable development goals. It will help countries realise their commitments as per the global emissions and climate targets and the global as well as country specific sustainable development goals by identifies energy sources, technologies and powerplants that can aid the energy transition by applying different research designs and methods.

The research has the following objectives:

1.3.1 Specific Objectives

- i. To identify the dimensions and indicators of sustainable energy for electricity generation.
- ii. Identify energy sources for sustainable power generation.
- iii. Identify power plants and conversion technologies for sustainable electricity generations.
- iv. To identify sustainability enhancing and enablers of sustainable power generation and supply
- v. Establish the sustainability of energy sources, power plants and energy conversion technologies within the dimension's energy sustainability.

1.4 Rationale of the Study

Energy demand, particularly electricity is ever growing globally mainly because of technological progress and electrification of geographical areas, electrification of processes and services that were previously not electrified, population growth and economic growth. Furthermore, electric energy consumption is directly related to economic development, population growth, and urbanization. To meet the growing electricity and other related forms of energy together with sustainability concerns in socio-political and economic issues requires new approaches, technologies, and concepts in energy management[12, 91].

The world's energy markets have set targets to achieve a net zero emissions by 2050, and many have subsequently made pledges just before the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change to cut down on greenhouse gas emissions. To achieve net zero emissions safely and economically can only be achieved by through implementation of policies, applying appropriate technologies, and taking the measures required[16, 92].

It is important to decarbonize the energy sector as a priority to achieve net zero emissions because it is the sector with the largest emissions and has capacity to decarbonize many other sectors. A major component in the zero net emissions strategy is the broad adoption of low-carbon technologies, like increased uptake of wind and solar PV and increased use of nuclear energy. It is necessary to have an integrated strategy to address net zero emissions (NZE) in the energy sector[92, 93].

Studies in [12] showed a correlation between electrification and the and greenhouse gas emissions. As an example, since 1990, the economic growth in China which was also associated with electrification of various sectors significantly increased the country's energy consumption. There is a causal relationship established between energy generation sources and carbon dioxide emissions in many studies [92, 93].

Electricity is an integral part the economy as it directly supports a wide range of services including health care, banking to transportation which makes power supply of paramount importance. The energy and power sectors are undergoing a wide range of fundamental changes like decarbonisation with growing share of variable renewables, growth in digitalisation which expands the surface cyberattacks. As a response, there is need for stakeholders to improve their frameworks for power security through updated policies, market design , and regulations [87].

It is technically feasible to keep the global temperature rise below 2 °C, but the global energy system must replace the present system that is largely dominated by fossil-fuels. The share of renewable energy must increase from about 18% total final energy consumption in 2015 to about two thirds by the year 2050 and the share in electric power generation should increase from around 25% to 85%. At the same time the energy intensity in the global economy should reduce by about two-thirds. Other measures include the lowering of total energy demand in 2050 to a level below what we had in 2015. It is possible to have renewable sources make up two-thirds of global energy mix by 2050, with better energy intensity[27].

The global greenhouse gas emissions continue to grow, amounting to 38 GtCO₂ for the year 2019, which represents a growth of 0.9% over the emissions for 2018. There is global commitment to reduce greenhouse gas emissions. For example, the US rejoined the Paris agreement in early 2021 and is committed to reduce greenhouse gas emissions by 50–52% by 2030 based on emissions for the year 2005 levels, while the European Union (EU) is committed to reduce emissions by 55% until 2030 based on the level of emissions for 1990 and additionally achieve climate neutrality by the year 2050. The power sector has been identified as a centerpiece in the commitment to achieve climate neutrality. This calls for expansion of variable renewable energy (VRE), increased use of battery energy storage

systems (BESSs) and power transmission. Others include the integration of stand-alone energy systems and more exploitation of renewable and low-carbon hydrogen are [6].

Fossil fuels account for over 60% of the global electricity production and account for over 80% of global energy consumption by the transport sector[3, 21, 94]. The contribution of this study includes formulation of a holistic electric power sustainability assessment approach based on the 5 dimensions of sustainable energy and electricity to enable long term as well as real-time planning and dispatch of power generation and supply resources and lay a foundation for planning and execution to achieve a global sustainable transition pathway that can be customised by individual countries and power systems. Various important targets have been set by the United Nations Sustainable Development Goals (UN-SDGs) for global achievement by the year 2030[53]. This study seeks to reduce the global greenhouse gas emissions by increasing the share of renewable energy sources by enhancing wider access to clean energy and responsible energy consumption spelt out in the SDGs-7, 12 and climate change mitigation SDG-13 that seeks to substitute fossil-fuel energy sources for renewable energy [53], [2].

Electricity production alone which remains dominated by fossil fuels as energy sources accounts for about one-third of global greenhouse gas emissions which puts it right at the centre of the global energy transition efforts. Provision of cleaner energy has an important role in raising the standard of living, thus the primary objective of enhanced deployment of renewable energy is not just to limit emissions and climate change but to advance economic development, improve access to energy, and improve energy security. Sustainable development can be achieved by use of sustainable energy and electricity delivery of affordable, sustainable, reliable and modern energy services[3] [95],

Energy transformation and sustainability is a challenge, for many countries particularly the developing countries. These challenges include a wide demand–supply gap, over-reliance on fossil fuels, and low access to clean energy[3, 29, 96]. The increase in electricity demand has introduced challenges in generation and distribution with increasing requirements for greater reliability, flexibility, efficiency, security, automation and both energy and environmental sustainability and use of smart grids can add significant value[97]. The smart grid technology has potential ability to enable a smooth transition to smart energy systems from traditional

systems leading to enhanced energy security and access to sustainable energy[56, 98]. A modern electricity grid should satisfy three challenges, namely renewable energy, electric vehicles, and control of energy demand while at the same time improve the quality of electricity supply and reduce costs[63].

Over 400 billion metric tons of carbon have been released to the atmosphere from fossil fuels combustion and cement production since the year 1751. Of these emissions, about 200 billion metric tons came from fossil fuel combustion emitted since the late 1980s. In the year 2014, the global fossil-fuel carbon emissions were estimated at 9,855 million metric tons accounting for about 0.8% increase in emissions over the 2013 emissions level which implied three years of modest growth in emissions [3, 61, 80]. The emissions trend shows that fossil fuel combustion and related activities for power generation and cement production in the manufacturing industry are leading sources of greenhouse gas emissions hence their use should be limited by promotion of decentralized generation and use of renewable energy resources[99-101]. This can be achieved using smart grids[12, 62, 82].

The traditional grid was designed to connect large central power plants with electricity distribution through a high voltage transmission. Over years, the traditional grid has grown from a transmission system with local and regional grids into a large, interconnected network system whose management is in the form of a centrally coordinated operating and planning procedures[3, 102]. The notable limitation of the traditional grid is that it only remains effective where the peak demand and energy consumption grows at predictable rates. The technology is effective in a relatively well-defined regulated operational environment making it difficult for the traditional grid to handle variable, and unpredictable load like variable renewables and grid connected electric vehicles [102, 103].

Increased decentralization and demand for micro grids has increased demand and hence need to increase the share of renewable energy resources which are variable and intermittent in supply. Electrification of transport has also led to increase in use of electric vehicles which need charging facilities that introduce significant number of variable loads to the grid while at the same time provide an opportunity for V2G (vehicle to grid power supply) which is also variable in nature. The grid must be highly resilient and smarter to effectively handle these variable electric loads and energy sources [68, 104, 105]. The demand for a resilient and

intelligent power grid is further compounded by growing popularity of variable electricity billing for efficient demand side management which additionally creates demand for smarter grids [67, 68, 106]. The use of smart grids has a role in the energy transition reduce emissions by facilitating efficient power distribution which ultimately reduces greenhouse gasses and pollutants like NO_x and SO_x from power plants[79, 97].

The traditional electricity grids have challenges related to managing expansion and operation of the transmission, generation and distribution in a dynamic and complex environment where significant variable and unpredictable electric loads and sources of generation have become increasingly important for the energy transition [21]. Amid this concerns, opportunities and challenges, for a highly resilient and flexible grid system will increase absorption of abundant but variable renewable energy sources and desirable electrification of transport systems hence contribute to national and global energy electricity security[21, 107]. Therefore, the future grid must connect all new sources of electricity, including renewables, extend grid coverage over thousands of kilometres deep into the interior and rural settlements with small but widely distributed load demands and limited related transmission and distribution losses. The solution to this challenges is a stepped up investment to modernize and digitalize electricity networks to guarantee secure, reliable and affordable power systems in the current energy transition to clean and renewable sources of power[108]. It is for these reasons that smart grids have shown a huge potential in transforming the energy systems towards sustainability.

The world has experienced considerable technological advances in electricity generation and supply, but new challenges continue to emerge particularly with absorption of variable and intermittent energy sources [61, 102]. This has led to continuous upgrading of the grid with new technologies which include development of high voltage equipment, advances in computerized monitoring, control, protection, and management of the grid with real-time operation and maintenance, increasing efficiency and cleanliness of power plants, advances in power electronics in the form of flexible alternating current transmission systems (FACTS) and advances in high voltage direct current (HVdc). These developments have created a conducive infrastructure and environment for transforming the traditional grid to an intelligent or smart grid[21, 102].

Concerns about greenhouse gas emissions and climate change are now at the centre of the international energy policy discourse[58, 78]. However, there are too many barriers to the deployment of energy that meets the sustainability requirements like competitive and reliable fossil fuels leading to fossil fuel domination of the energy mix[81, 109, 110]. Through their ability to increase the uptake of renewables by the power grids, smart grids can help reduce emissions and hence global warming potential and increase power system resilience and reliability[111, 112].

The growing demand for electricity and development of smart grids are providing significant opportunities for home-based energy management [69]. Important qualities of grid electricity include grid reliability which is a measure of the ability of the grid to meet customer needs and expectations in terms of quality and demand quantity. Reliability is a very important dimension of the sustainability of the power system grid[113-115]. The security of energy supply requires a flawless and error less power system that guarantees a continuous supply of electricity to consumers. Therefore measures like use of the smart grid is the ultimate choice due to its ability to detect faults, prevent failure and allow self-healing of the power system[97]. On the other hand, the traditional grid has challenges with integration of renewable resources, support and integration with micro grid and demand response capability. The main drivers of demand for smart grids are ever growing electricity demand and supply, growing level of variable loads and variable renewable energy sources in grid power generation[82, 97]. This is because smart grids can monitor, store data, and initiate real time corrective measures to these challenges [61, 74, 97]. This study will among others examine the role of smart grids and smart energy systems in the energy transition.

Smart energy systems like the Smart grid technology presents unprecedented opportunity to transition the energy industry into an era of high availability, reliability, and efficiency. This will enhance economic and environmental health of both developed and developing world economies[3, 12, 29, 64]. Power supply with the traditional grid is characterized by electricity disruption like blackouts which can have significant negative impact on almost all industries and services like banking, traffic, communications, water, and security. Worse is power outage in winter, which can leave consumers without heat. With a smart grid, resiliency is added to the power system making it better prepared to handle or accommodate emergencies like severe storms, earthquakes, and terrorist attacks[63, 116]. The smart grid is managed in a more

flexible way to manage constraints like variability and intermittence of energy resources and support of variable loads like electric vehicles[61]. The constraints can change the current system, in which real-time equilibrium is ensured by adapting production to consumption, to one in which adjustment is done more by demand converting the consumer to more important actor in power system control [28]. Therefore smart grids combine a demanding business environment and new technological advances that can transform the energy sector[63].

1.5 Lifecycle Assessment of Energy Sustainability

The transition to renewable energy sources and green technologies for power generation and storage will help in mitigating the climate change from greenhouse gas emissions. The main sustainability challenge for the transition is the dependency on critical materials, processes and other resources that have significant environmental impacts. Beyond the global warming concerns, we have serious sustainability concerns like loss of biodiversity, water scarcity, environmental pollution, and energy security that should equally be addressed during the transition [2, 117].

The issues of energy and environment are seriously interconnected and need comprehensive analysis and understanding of resource management strategies and their consequences. As an example vital water resources depletion and contamination is related to possible shortages in power generation, distribution and use while at the same time the supply of water needs energy[117]. There is therefore a need for a system perspective to locate and quantify the impact of human activities and processes on the environment. The Life cycle assessment (LCA) is one of the most inclusive analytical techniques to analyze sustainability tradeoffs and benefits resulting from complex energy and environmental systems[29, 117].

1.6. Energy Transitions

The turning point for accelerated energy transition is worsening climate emergency, ongoing energy crisis and growing political uncertainties globally. Energy transition refers to a continuous process that requires long-term energy strategies and planning focusing on application of appropriated energy technologies to achieve a net-zero emissions. The energy transition requires an integrated, people-centered approach with application of all available energy technologies in the transformation of local and national energy systems[118-121]. The growing concerns over global warming highlight the importance of the global transition

towards a “green economy” through less consumption of fossil fuel and greenhouse gas emissions. Energy transition refers to the shift from fossil-based global energy sectors dominated by oil, natural gas, and coal to renewable energy sources like solar, wind and low carbon sources like nuclear lithium-ion batteries[118]. An energy transition is a broad shift in technologies and behaviors to enable the replacement of one source of energy with another. According to the transition is defined as the process of changing from one state or condition to another over a given time. This transition can occur in firms, cities, individuals, regions, and countries, and can be based on incremental or transformative change[1, 3]. The world has so far witnessed three typical energy transitions. The first transition involved replacement of wood with coal as the main energy source. In the second transition, oil replaced coal as the dominant energy resource. In the third transition, there is global commitment to replace fossil fuels with renewable energy. As in 2018, 80% of the global energy was derived from fossil fuel energy resources with 36% being petroleum, 13.2% for coal, and 31% was from natural gas[122]

1.6 Policy Issues in the Energy Transition

In as much as the energy transition remains technically and economically feasible and beneficial, policy initiatives are necessary to steer the global electricity transition towards a sustainable energy and electricity systems[26]. The focus areas where policy and decision makers should act are as follows.

i. Develop a Strong Synergy Between Energy Efficiency and Renewable Energy.

Policy maker’s policy design policies that combine the effect of bulk of energy-related decarbonisation needs by 2050 in a cost-effective manner through efficient energy production and use.

ii. Develop an Electric System in Which Renewables Provide a Higher Share of The Energy Mix.

There is need to transform the global energy system through fundamental shift in the way electric power systems are conceived and deployed. This calls for long-term system planning and a shift to policymaking that is more holistic and coordinated across all sectors and nations. There should be timely deployment of infrastructure and the redesign of rules and regulations to achieve cost-effective integration of solar and wind generation on a large scale. With their

massive potential and renewability with negligible emissions and environmental impact, wind and solar should be made the backbone of electric power systems by the year 2050 to meet the targets set in the Paris agreement[26, 123].

iii. Accelerate Electrification in Transport, Building and Industry.

There is need for deep and cost-effective decarbonisation of the transport and heat sectors by electrification with the bulk of power coming from renewable electricity. Where it is not possible to electrify transport, industry, and buildings, then other renewable solutions will have to be adopted. Alternative sources of energy for direct use include modern bioenergy, solar thermal, and geothermal heat applications. The realization of this shift needs the deployment of an enabling policy framework and development of supporting technology and other related initiatives in urban planning, building, transport and industrial sectors[26, 123].

iv. Foster System-Wide Innovation

There is a need to have continued technological innovation to achieve a successful global energy transition, just the same way new technologies have played a leading role in renewable energy development and deployment. Innovation effort must cover a technology's full life cycle, that includes demonstration, technology deployment, commercialisation, and final disposal. It is worth noting that innovation is broader than technology research and development (R&D) as it includes new approaches to existing energy systems and markets and development of new technical and business models. There is need for coordinated effort by regional, national governments, national and international actors, and the private sector to deliver the needed innovations to facilitate energy[26, 123].

v. Align Socio-Economic Structures and Investment with the Transition.

There is a need for a globally integrated and holistic approach by alignment of socio-economic systems with the requirements of the energy transition. Implementation of the energy transition requires investments, in addition to those already incurred with respect to the adaptation to climate change. Faster realization of the energy transition would lower the climate change adaptation costs and in addition to reduced socio-economic disruption. This calls for alignment of the financial systems with broader sustainability and energy transition demands while noting that today's investment decisions made define the energy system of many years ahead. For smooth investment in energy transitions, there is need to allow urgent

flows of capital investment to low-carbon solutions, to avoid locking economies into a carbon-intensive energy system and to minimise incidents of stranded assets[22, 23]

A smooth and successful energy transition calls for establishment of regulatory and policy frameworks that give all relevant stakeholders a clear, firm, and long-term guarantee of energy systems transformations to meet the emissions and climate goals set. This will create economic incentives that are aligned to the environmental and social costs of fossil fuels and remove barriers to accelerated deployment of low carbon energy systems and solutions. Energy transition would require increased participation of both private and public institutional investors as well as community-based finance who should be facilitated and motivated with relevant incentives. The requirements and specifications of distributed investment needs including energy efficiency and distributed generation need to be addressed within the socioeconomic structures and investment transformation[26, 123].

vi. Ensure that Transition Costs and Benefits are Distributed.

The whole society should be involved in a collaborative manner in the process to achieve the desired transition. Effective participation is only achievable if the benefits of the energy transformation are shared and the transition itself is implemented in a fair and just manner. A key requirement and component of a fair and just transition is the universal energy access. There is a need for the transition scenarios and planning to incorporate access and convergence factors in the transition because there are huge disparities presently in availability of energy services, hence need for energy services to converge in all regions[26].

A successful energy transition will require the promotion and facilitation of a social accounting framework which enables and visualizes the transition contributions and obligations from the stakeholders. There is a need to make advances in the definition and implementation of a fair context to share costs of transition while at the same time promoting and facilitating structures which enable fair distribution of the benefits of the transition. A just transition should explicitly be addressed with consideration from the onset the macro, and micro levels, which enables the creation of structures needed to provide alternatives that allow parties who have been trapped into the fossil fuel dynamics to participate effectively in the energy transition.

1.7 Energy and Electricity Planning

In grid power systems, several power plants are deployed to meet consumer demand in an interconnected system [84]. The planning, design and dispatch of a power system and power plant as a unit takes into consideration a number of parameters [124]. These parameters include the total installed capacity of the power plant and power system, the size of each generating unit within power plants, cost of operation and maintenance of power plants among others[32].

Various power plant performance factors and indicators are used in the planning, operation, and management of electricity generation. They include load factor, capacity factor, average load, reserve factor, demand factor, diversity, plant use factors and plant utilization factors [84]. These parameters define the characteristics of power plants and a power system. The planning for generation is based on a daily load curve from which load duration curves are developed. These load duration curves can be used in sizing power plants and allocating generation based on their characteristics. The load on a load curve and load duration curves is divided into three parts namely, base load, intermediate load, and peak load. Base load is load that is available on a power system throughout the duration under consideration [3, 124].

The stability of the electric power grid is maintained through real time balancing of electricity generation and electricity demand. The power sector needs robust Energy Management Systems (EMSs) and optimization techniques for flexibility to accommodate multiple storage technologies, new applications, and the ability to operate in evolving market structures [125]. Different power plant characteristics are desirable for specific type of load, and with variable nature of electricity demand, the system must have flexibility and be capable of quick dynamic response[68, 84]

Planning energy supply mix is a very challenging undertaking which requires planners to consider various drivers and decision criteria. This study addresses the multi-period energy planning problem with carbon dioxide (CO₂) emission constraints and cost constraints with energy sources ranked in the order of sustainability. The load curve and duration curve are the primary tool used in analysis of electric power utility operations and for the purpose of planning new power plants[2, 3]

The techno economic analysis of power system solutions for customers is generally based on the peak demand, average power demands and actual energy consumption. Power demand and supply varies over the time of the day which poses challenges to utility operators, suppliers and even consumers of electricity. Customer electricity profiles can be applied for improved techno-economic analyses of energy solutions [86]. Many factors also combine to increase demand for power while old power plant loose capacity and are finally retired hence the need for new capacity to replace old power plants and meet new demand capacity[2, 61].

The sudden oil glut of the 1973 to 1974 period caused by an oil embargo set in motion interest in alternative sources of energy. Prior to the oil crisis, major world economies had oil dominating the energy consumption profiles, which exposed them to the supply limits. Stakeholders who included policymakers and researchers started exploring the possibility of substituting oil for alternative sources[53].

1.8 Sustainability of Energy Resources and Electricity

It is through the cumulative effect of the Stockholm, Rio, and Johannesburg conferences, the notion of sustainable energy development (SED) was made a very important factor in the sustainable development by linking energy to the environmental dimension in the Stockholm conference, economy in the Rio conference and society in the Johannesburg conference[2, 126]. Sustainable energy, just like sustainable development requires significant changes in the way things are done and the exact things that we do with effects on the industrial, production, social infrastructure, and value systems. The development of clean energy would unlock many challenges to sustainable development[21, 44, 58]. Sustainability is a major concern today as a direct result of the serious concerns over the climate change, of which electricity generation is an important contributor[127].

Electricity is a critical product needed to support life, welfare and global sustainable development[128]. Currently, humanity is faced with a significant challenge to realize new sustainable development Goals (SDGs) by the year 2030 [101, 128]. Sustainable development and its correlation with energy became a significant global concern and issue in the 2002 Johannesburg world summit on sustainable development[129].

1.8.1 Sustainability and Dimensions of Sustainable Development

Sustainable development should facilitate social equity, prevent environmental degradation and while maintaining a sustain a sound economic base. There is a need for sustainable preservation of natural capital to guarantee sustained economic production and equity in intergeneration equity in resource consumption[2]. It is also necessary to fulfil basic health and participatory democracy in energy resource planning and exploitation to ensure sustainability. Sustainable development has got three main dimensions, namely economic, social, and environmental sustainability, but energy sustainability extra dimensions of technical, and political or institutional sustainability[3, 12].

Sustainability broadly means the ability to maintain or “sustain” over time. Although the precise definition of sustainability vary from person to person, field to field, by and large, all the definitions capture three distinct dimensions, namely social, economic, and environmental, which are also referred to as the three pillars, three components, or three aspects of sustainability[3, 130]. Sustainability is regarded as a multi-disciplinary, problem-solving approach to create a social system that meets the needs of the present generation in a way that does not compromise the ability of future generations to meet their own needs without causing ecological imbalance and disturbance. The sustainability framework challenges individuals and institutions to consider the interdependent nature of human lives, the natural environment, our communities and the economy and especially the improvement of these relationships[130].The pillars of sustainability are demonstrated in Figure 1-3.

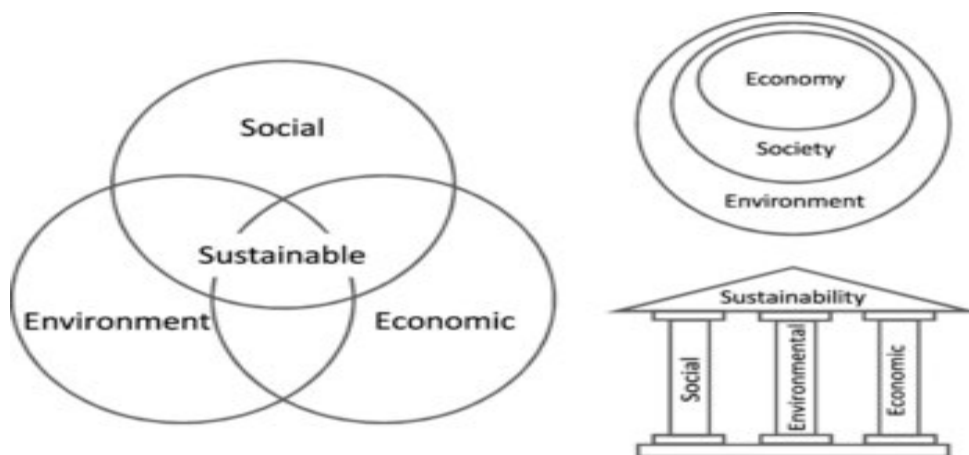


Figure 1-3 :Sustainability Diagrams. Left, three intersecting circles, Right, literal ‘pillars’ and a concentric circle approach[130].

From Figure 1-3, it is noted that sustainability encompasses three dimensions or pillars, namely economic, social and environment.

1.8.2 Dimensions of Sustainable Energy

The establishment of the most appropriate energy systems in an electricity mix is considered as a strategic approach in realization of sustainable development[131, 132]. Energy and power generation systems can be assessed by a five-dimensional approach consisting of environmental, economic, social, technical and institutional sustainability as a strong measure of energy sustainability[2, 131]. Therefore, sustainability in energy development seeks to achieve technical sustainability, political or institutional sustainability, social sustainability, environmental sustainability, and economic sustainability which is greatly realized by the development and use of renewable energy resources[3, 133]. Figure 1-4 illustrates the 6 main dimensions of energy sustainability.



Figure 1-4: Dimensions of energy sustainability[3]

Figure 1-4 summarizes the main dimensions of energy sustainability, particularly electricity. The main dimensions of sustainability in energy development and consumption are environmental, social, political, economic, and technical sustainability.

1.8.2.1 Technical Sustainability

For evaluation of energy or electricity sources, a number technical and operational indicators have to be analyzed[134]. The typical technical evaluation criteria for energy systems and sources include efficiency, exergy efficiency, primary energy ration, system reliability, maturity of technology and safety considerations[135]. Other important power plant performance indicators in power plant generation are specific fuel consumption, specific emissions, power plant availability, load factor, among others.

The transformative and disruptive potential of rapid technological changes, and the danger of using primitive technologies should be avoided for a sustainable transition. Even with advanced science, technology and innovation policies, and technologies, it is unlikely to deliver progress regarding global development unless the environment nurtures learning and innovation for effective management of innovation systems. Both national and international policies should promote international technology assessment, foresight and cooperation including collaborations and technology transfer. This cross border partnerships and cooperation will facilitate rapid sustainable energy development[136].

1.8.2.2 Environmental sustainability

Environmental sustainability is concerned with managing the negative impact of energy production and use to society and to magnify or extend the good ones. The environment should only be allowed to absorb what it can contain, naturally or artificially[15]. Environmental sustainability is concerned with the integrity of natural environment and its ability to remain resilient and productive in support of humanity[2, 126]. Environmental sustainability is further concerned with the integrity and carrying capacity of the natural environment to sustain humanity as a waste sink and source of raw materials[137]. Thus, the environment or ecological dimension of sustainability is concerned with preservation of the environment and habitats, especially against the impacts of waste disposal, excessive consumption of earth's resources, and greenhouse gas emissions. The gases that lead to global warming include carbon dioxide, methane, and nitrous oxides. Carbon emissions in the atmosphere have increased from about 280 ppm by volume during pre-industrial times to over 400 ppm today representing more than 40% increase. In the United States, fossil fuel consumption results in average annual emission of about 5.3 billion metric tons of CO₂ into

the atmosphere[138]. The origin of these carbon emissions is from energy consumption, non-energy use and industrial processes like iron and cement production[2, 3].

An environmentally sustainable energy system should maintain a stable resource base, avoid resource over-exploitation, and avoid depleting non-renewable resources through development of adequate substitutes through approaches like biodiversity maintenance, atmospheric stability, and other ecosystem functions that are not necessarily economic resources[2, 3, 139].

1.8.2.3 Economic Sustainability

Economic sustainability in energy and electricity production and consumption is the ability to meet energy demand in a cost-effective manner. It is also a measure of access to requisite financing for energy resource development[12]. The cost-effective operation will ensure that the energy system is economically viable and feasible and hence makes the investment attractive to investors and financiers [96, 133]. All economies are made up of markets where transactions are made. The main activity in an economy is production of goods and services, distribution and consumption[137]. Therefore, the economic dimension of energy sustainability is concerned with the viability of individuals and organizations, products, and services in production and consumption of energy or electricity, distribution, and interactions[2, 39].

1.8.2.4 Social Sustainability

Social Sustainability is concerned with the well-being and longevity of a community. A community consists of people and places where they live; hence is both a social environment and a physical environment. Human beings live in a linked system of humans and nature such that you cannot solve environmental issues without considering humans issues and vice versa[2, 3, 130]. Social sustainability addresses the rights of the community as measured by its level of social acceptance and access to the energy resource and systems[15]. Social sustainability is the ability to preserve desirable social values, institutions, traditions, and social characteristics of society before and after an intervention or investment. It addresses aspects like labor practices, variance in production standards, and promotion of equity among all people[140-142]. Social sustainability can be achieved by the selection and development of options that provide adequate power and employment to local communities and that don't

interrupt or interfere with their established way of living and value system [126, 133, 143]. Therefore, social sustainability ensures that people are important since development is basically about the people themselves. Important principles used to realize social sustainability include accountability, empowerment, participation, cultural identity, and institutional stability[137].

Therefore, social sustainability of the energy transition is concerned with the value of energy to the community, democratic participation, direct benefits through addition of human and social capital, job creation and other community benefits through activities like corporate social responsibility and respect for local customs, traditions, and beliefs.

1.8.2.5 Political and Institutional Sustainability

The political or institutional dimension of energy sustainability is concerned with governance of sustainable energy transformation at all levels. This is achieved by setting and implementing policies and regulations with different political institutions influencing governance choices[144]. This implies that the political dimension of energy sustainability is concerned with the strategic planning and definition of the energy system and related systems and processes. Therefore, political sustainability concerns address the future structure and indicates some issue on political stability and foreign policies of the energy system [2, 3, 133]. For development to be sustainable, there is need for adequate management of the tradeoff between social equity, protection and integrity of the environment, real economic development and progress and preservation and use of natural resources for equitable use by all [145]. This can only be achieved effectively when we have the political will from all if not many nations and groups that have power to influence energy policy [141].

The institutional dimension of energy sustainability defines the role of local participation in the control and management of energy resources and energy systems[141, 142]. The institutional dimension embodies elements such as local ownership, participation, local contributions, local skill base, local policy and regulation, protection of investors and consumers and sharing of resources and benefits accruing. The institutional dimension defines the system structure and framework of processes, systems and policy decisions which affect energy projects [15, 126]. There is evidence that highly or adequately institutionalized countries with efficient and effective energy related institutions are more successful in

managing the energy transition. The main reason is that these institutions encourage innovation, efficient resource allocation, participation and desirable policy, legal and financial measures and instruments which are enablers of sustainable energy transition[2, 3, 146].

1.9 Energy Sources for the Transition

Energy is scientifically defined as the ability to do work and exist in different forms. Energy takes many common forms like kinetic energy of a moving object, the potential energy stored by an object, the elastic energy stored in a solid object, chemical energy from chemical reactions, the radiant energy carried by electromagnetic radiation, and the internal energy which is contained within a thermodynamic system. All living organisms need energy and release it in different forms and hence energy keeps life going, drives machines in industries, warms homes and keeps the economy running and growing. Energy in the form of electricity is easier to control and transport over greater distances and can be converted to other forms of energy like heat, light and can be stored in batteries for later use. These explain its widespread global use as a form of energy for industrial and domestic use.

Different energy sources can be used for power generation, e.g., hydro from water, solar energy from the sun, wind energy, wave, ocean thermal, tidal energy, hydrogen, oil, nuclear energy, biomass, biogas, biomethane, natural gas etc. Electricity is the movement of electric charge whose intensity is measured in amperes. Current is moving charged particles; most commonly these are electrons, but any charge in motion constitutes a current. Electric current can flow through electrical conductors for delivery to electrical devices for use e.g. heaters, motors[16]

1.10 Power Plants and Power Generation

Electricity is produced by electric motors through electromagnetic induction and in some cases direct conversion like in solar photovoltaics. A power plant is an assembly of machines, devices, and systems for production of electricity. Different energy sources require different power plants which also have different performance characteristics that define their ideal applications. The same power plant can use different energy sources, but they should be adopted to handle and exploit the specific energy resource. Power plants can be classified based on the source of energy used e.g., wind power plants, solar power plants, coal power plants and nuclear power plant. They can also be classified based on the prime mover used to

drive the generator e.g., diesel power plants use diesel cycle engines, gas turbines power plants use gas turbines as prime mover. Power plants can also be classified based on their role on the load demand curve e.g., base load, intermediate and peak load power plants. The fluctuating nature of demand calls for use of a mix of dispatchable and non-dispatchable power plants. Dispatchable power plants can be controlled, switched on and off based on need and these are usually the fossil fuel power plants and are ideal for emergency and peak power supply. The non-dispatchable power plants consist of variable renewables like wind and solar which can only be used when the energy resource is available. This additionally affects the performance characteristics including efficiency, emissions, and cost of power. Therefore, careful selection of power plants influences sustainability power generation[16, 32]. In this study, the various power plants and conversion systems for power generation are identified and discussed.

1.11 Sustainability Enhancing Technologies

Different devices and systems are required to ensure delivery of quality and safe power. The fluctuating nature electricity demand and energy supply from variable sources and growing global pressure to increase the use of renewable sources, most which are variable and intermittent calls for adoption of technologies that enhance the uptake of these resources while at the same time maintaining and improving the power system reliability, resilience, and stability[147]. These systems and technologies include the smart grids, energy storage systems like grid scale storage batteries, demand side management and behind the meter management which enables prosumers, energy and power system models and modelling tools, decentralized generation and microgrid technologies. In this study, the various sustainability enhancing systems, technologies and concepts are identified and discussed within the confines of energy sustainability and the transition[16, 32].

1.12 Research Methodology

This study adopted a mixed research design that included case studies, systematic reviews, performance analysis and review, preliminary design and analysis of energy systems and comparative analysis. The research design refers to the overall strategy and analytical approach adopted to integrate, coherently and logically, the different components of the study, in a way that the research problem is thoroughly investigated. A research design constitutes the blueprint for data collection, measurement, and interpretation of data and information

within the confines of a research problem which determines the type of research design chosen. The research design in this research facilitates evidence collection which enables effective, logical, and unambiguous address approach to a research problem[148].

1.13 Contributions

Grid electricity which is the focus of this study is a mix of electric power produced from different energy sources converted to electricity through different power plants and energy conversion systems. This study therefore targets all possible sources of electricity considering their characteristic properties and ability to contribute to the grid load which is always dynamic in terms of demand and hence supply making the study unique as it takes a wholistic view of the energy and power sectors to identify candidate sources of energy and power plants to use and how to use them in the energy transition which seeks to sustainably limit greenhouse gas emissions and global climate change. Because of the dynamic nature of grid electricity demand and supply that is difficult to meet with non-dispatchable renewable source alone, the study positively considers the positive aspect of the fossil fuel sources of energy and power plants for their role in stabilising the grid. The study adopts a neutral view of all power plants and energy sources and considers both current and future options that effectively within five dimensions of energy sustainability which led to a widened scope and wholistic study compared any other previous research. This study provides a planning manual and exhaustive guidelines for policy makers, planners, authorities, and governments seeking to sustainably transform their current and future energy and power systems. This thesis lays a solid foundation with critical information needed by energy and power system modellers as well as utilities in planning and deployment of current and future power generation resources. This thesis is a sustainable energy and electricity manual for the global energy sector transition in the journey towards the net zero emissions by the year 2050.

1.14 Organization of Thesis

This thesis organized as follows. Chapter 1 contains the introduction to the subject of sustainable development, sustainable energy and electricity and their sustainability. Chapter 2 presents literature review; chapter 3 presents the research methodology and energy sustainability measurement indicators and tools. Chapter 4 contains the energy sources for power generation, chapter 5 presents power plants and energy conversion systems for power generation, chapter 6 presents the various technologies and concepts that enhance energy and electricity sustainability, chapter 6 presents the technologies, infrastructure, and concepts for the energy transition. Chapter 7 presents bagasse and cane trash as sustainable energy resources, chapter 8 presents the feasibility of grid-based bagasse cogeneration, Chapter 9 presents geothermal wellhead power plants in the energy transition, chapter 10 presents case studies of waste to energy pathways, Chapter 11 presents sustainability measures for fossil fuel power generation options, chapter 12 presents carbon capture and sequestration as a sustainability measure through emission withdrawal, chapter 13, presents biomethane production and applications as a sustainable energy resource, chapter 14 presents hydrogen production and applications as a sustainable energy resource, chapter 15 presents fuel cells and their role in the energy transition, chapter 16 presents smart grids and microgrids as transition infrastructure, chapter 17 presents energy storage and role in sustainable energy transition , chapter 18 presents the role of transport sector electrification in the energy transition, chapter 19 presents sustainability assessment of energy sources for the energy transition, chapter 20 presents sustainability assessment for power plants and energy conversion systems for the energy transition, chapter 21 presents results and discussion, while chapter 22 present conclusions and recommendations.

1.15 Chapter Conclusions

This chapter provides a background overview of the research undertaken. It was shown in this chapter that the energy sector is a leading contributor to global greenhouse gas emissions, and this prominence emerged during the industrial revolution. Global CO₂ emissions remained constant between 1751 and about 1840 when they started increasing. The atmospheric concentration increased slightly between 1751 and 1960 where the rate increased significantly to the year 2022 mainly due to increased use of fossil fuels and growth in industrial activity.

Therefore, it is the entry of fossil fuels into the energy mix and the industrial revolution that triggered rapid increase in CO₂ emissions as the level of industrialization developed. The study showed that the Paris Agreement made a commitment to limit global warming to well below 2 °C and then to pursue efforts to limit the rise to 1.5 °C relative to pre-industrial times, but the gap report on emissions shows that world is not on track to reach the Paris Agreement goals and global temperatures targets and that the temperature may reach 2.8°C by the end of the century which demonstrates the serious problem of emissions and climate challenge facing humanity, with emissions having grown by 50.56% from 277 ppm in 1750 to 417.06 ppm by the end of the year 2022. Since sustainable energy is the solution to this global challenge, the chapter presents energy sustainability as the key focus of this study and identifies dimensions energy sustainability as environmental, social, political, economic, and technical sustainability with the objective being to sustainability limit the use of fossil fuels. Among the critical areas presented in this chapter is the research problem, which addresses the need for development and use of sustainable energy and production of sustainable power to support the global energy transition and attainment of the sustainable development goals. The objectives, the proposed methodology, the motivation/rationale, and the contribution of this study were presented. This chapter also highlighted the structure of the thesis and provided an overview of the study.

CHAPTER 2:

LITERATURE REVIEW

2. Overview

This chapter presents a comprehensive literature review on energy related emissions, energy sustainability and role in sustainable development, the global climate change, and its consequences. Additionally, the role of sustainable and renewable energy in the energy transition is discussed which lays out the general context of the research in terms energy sustainability in the unfolding energy transition. Most of the information is a summary of the authors related publications listed in this dissertation as published and currently under review for publication. The entire chapter is also under consideration for publication as a book chapter. This chapter reviews the literature to support the objectives and methodology of this study. It consists of energy and related environmental issues, greenhouse gas emissions and their sources as well as their global warming potentials. This chapter presents the role of energy in greenhouse gas emissions, global warming, consequences of climate change and mitigation measures. With sustainability being the focus of the energy transformation in this research, the concept of energy sustainability is presented in this chapter with discussion on energy and electricity sustainability. The main elements of greenhouse gases, their sources by sector and composition as well as the global warming potential of various greenhouse gases are presented and analyzed. The role of renewable energy and nonrenewable energy sources and challenges is highlighted in this chapter. The concept of sustainable development and the role and characteristics of sustainable energy is presented with the analysis within the five dimensions of sustainable energy that form the basis energy and power generation planning for sustainability. The content in this literature review is published in the authors publications [1-3, 12].

2.1 Introduction to Energy and Environment

Energy is a critical requirement for sustainable development and therefore optimum selection of low carbon and green energy sources remains a serious challenge for all developing and developed countries[149]. To realize green power generation, environmental, technical social, institutional, and economic dimensions should be used as a selection and development criteria

for sustainable energy and grid electricity planning. Electricity and other energy resources are very important inputs from the economical aspect and human well-being to develop a good framework of sustainability for cleaner and stable global environment and economies. While choosing or selecting energy sources for development or exploitation, technology and cost play a crucial role in modern economies and societies [132, 149]. With continuous increase in global population and socio-economic activities leading to increased urbanization, and industrialization around the world, demand for natural resources and energy is gradually increasing[131]. It is notable that the world's population has grown 2.5 times since 1950, while energy demand for energy has grown 7 times[135]. These increasing energy demand is mostly met by fossil fuel combustion and nuclear power[150]. Apart from rapid growth increase in the global energy demand, other challenges are depletion of fossil fuel reserves, their price volatility, and global climate change have attracted much attention to renewable energy sources. As a result, many countries have adopted policies to support the growth of renewable energy sources and other sustainable energy measures in the energy transition [131].

Climate change is real and is here with us hence the need to pay serious attention to mitigation measures. In the year 2018, the world encountered 315 incidents of climate change related disasters that affected 68,500,000 million people, causing an economic loss of US\$ 131.7 billion [151]. The climate related disasters are mainly in form of drought, floods, wildfires, and storms. These disasters are a threat to humanity as they affect critical sectors like health, agriculture, water, energy, and human settlements[151, 152]. Electricity as a form of energy is extremely important for socioeconomic development. Global electricity generation stood at 4114 GW in 2005 and increased to 5699.3 GW in 2014 and it continues to grow annually. Fossil fuel-based electricity accounted for over 60% of this generation in 2014 and 42% of CO₂. There is need to develop evaluation index system and models for sustainable electricity generation[153]. According to the emissions gap report prepared by The United Nations Environment Programme (UNEP) for 2019 noted that the total greenhouse gas emissions in 2018 was about 55.3 GtCO₂e, Further analysis of this emissions showed that 37.5 GtCO₂ came from fossil fuels combustion in the energy generation and industrial activities[154].

The combustion of fossil fuels releases significant quantities of large amounts of greenhouse gases mainly in form of carbon dioxide (CO₂), Sulphur dioxide (SO₂), Nitrous oxides (NO_x).

These gases cause global warming and climate change which threaten the very existence of life on planet earth. This concern is the main motivation behind sustainable energy development by use of renewable and low carbon clean energy sources especially solar, wind, biomass, and hydro. These renewable and low carbon sources improve and widen power supply, enhance long term access and utility in energy production, decrease dependence on fossil fuel, and reduce carbon emissions[155, 156].

There is a need for everyone to have sufficient access to energy resources and services since energy is a pillar for human survival, wellbeing, economic progress, and alleviation of poverty in society. The challenge is that energy systems are associated with environmental impacts which vary in magnitude from one source to another and one use and process to another. Fossil fuels continue to dominate current energy systems and therefore significantly contribute to the global to global greenhouse gas emissions to the atmosphere. To realize the global climate targets and avoid destructive climate change, there is need for a global transition in electricity generation, transmission and distribution and consumption. Humanity must strike a balance between developmental needs and the environmental conservation and protection[157].

The overall objective of the Intergovernmental Panel on Climate Change (IPCC) is to stabilize the atmospheric air carbon concentration. The target to facilitate this is a concentration of 350 parts per million (ppm) for CO₂ while maintaining temperature rise of 2°C temperature change above the preindustrial level. This was adopted by the G8 and G20 group of nations and it implies having atmospheric level of 400-450 ppm of CO₂ as the limit[3, 33]. Therefore, the main challenge in energy resources exploitation is developing an optimized mix of energy sources in the light of the key challenges of energy security, affordability, security, and sustainability on real time basis. Technologies and strategies like smart grid, optimization techniques and other measures are needed to increase the share of variable renewable energy sources in both the total energy and electricity sources mix with very minimum use of fossil fuels and other high carbon energy sources of energy with increased investment in energy conservation, efficiency and saving at consumption level[22, 23].

As the sun warms the land and ocean surfaces continuously, they continuously radiate thermal infrared heat energy. Greenhouse gases absorb heat and release it gradually. It is this

greenhouse effect that warms the earth and keeps its average annual temperature above the freezing point of about 60°F[8]. However continuous increases in greenhouse gases have tipped the Earth's energy out of balance, with trapping of additional heat energy causing raise in Earth's average temperature. As a greenhouse gas, carbon dioxide absorbs less heat per molecule than many other greenhouse gases like methane or nitrous oxide, but because it is more abundant and stays longer in the atmosphere much longer, its effect is significant. it also absorbs thermal energy of wavelengths that cannot be absorbed by water vapour meaning it adds to the overall greenhouse effect in a different way. Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise. Carbon dioxide also dissolves into the ocean and reacts with water molecules to produce carbonic acid which lowers the ocean's pH., The pH of the ocean's surface waters has dropped from 8.21 to 8.10 since the beginning of the Industrial Revolution. A drop of 0.1 may not seem like a lot, but the pH scale is logarithmic; a 1-unit drop in pH means a tenfold increase in acidity. A change of 0.1 causes about 30% increase in acidity of the ocean. The biological effect of ocean acidification is interference with marine life's' ability to extract calcium from the water to build their shells and skeletons [8].

The global Carbon dioxide concentrations have been rising mainly due to fossil combustion. Fossil fuels took many millions of years to form through photosynthesis, but through combustion, the same carbon dioxide is returned to the atmosphere in just a few hundred years of use. The last time the atmospheric CO₂ amounts were relatively higher was about 3 million years ago, when temperature was 2°–3°C (3.6°–5.4°F) above the pre-industrial era, and while the sea level was 15–25 meters (50–80 feet) higher than it is today[8]. Figure 2-1 shows the changes in atmospheric composition of carbon dioxide between 1970 and 220.

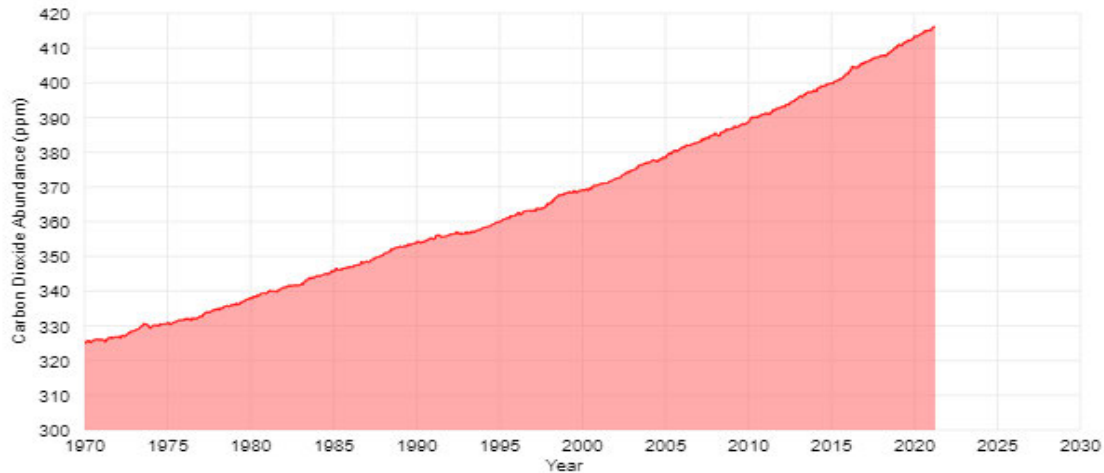


Figure 2-1: Changes in carbon Dioxide concentration between 1970 and 2020 [3, 8]

From Figure 2-1, it is noted that emissions concentration increased from about 325 ppm in 1970 to about 415 ppm in the year 2020. Human activities have led to increased concentration of atmospheric hence increased greenhouse effect. The global average amount of carbon dioxide reached 409.8 ppm in 2019. The annual rate of increase in CO₂ in the atmosphere is about 100 times faster than previous natural increases over the past 60 years e.g. last ice age 11,000-17,000 years ago. Additionally, the ocean has absorbed enough carbon dioxide to lower its PH by 0.1 units causing a 30% increase in ocean acidity [8].

There is growing urgency for large, rapid, and sustained greenhouse gas emissions reductions to avoid the danger of global warming. These calls for emission reduction in all sectors especially heavy polluters like transport, agriculture, and power generation. With power generation accounting for over 40% of total emissions, availability of low carbon substitutes and capacity of electricity as an energy carrier, emission reduction will have a significant global impact [41]. Whereas the costs Solar PV and wind have been reducing, they are highly variable and unpredictable which is a real challenge for a secure and reliable electric power system operation and maintenance as their deployment needs highly dispatchable generation capacity on standby which is conventionally supplied by coal, gas and diesel affected by interruptions from plant failures, and to fuel supply interruptions, droughts, and price fluctuations [42]. Electricity systems are witnessing a profound transformation, with a greater role for smarter grids going hand in hand with increased solar and wind deployment. Electricity grids i.e., transmission and distribution systems provide the bedrock of today's and

tomorrow's power systems, enabling electricity to flow and all sources of flexibility to contribute to electricity security. Grids expansion must accelerate over the next decade to connect all new sources of electricity, including renewables, extending grids by 16 million kilometres, 80% more than over the past decade [43]. This calls for optimum deployment of electricity power plants and infrastructure.

The emission of greenhouse gases (GHGs) and their implications to climate change have sparked a global interest in understanding the relative contribution of the electrical generation industry. According to the Intergovernmental Panel on Climate Change (IPCC), the world emits approximately 27 gigatons of CO₂e from multiple sources, with electrical production emitting 10 gigatons, or approximately 37% of global emissions. In addition, electricity demand is expected to increase by 43% over the next 20 years. This substantial increase will require the construction of many new power generating facilities and offers the opportunity to construct these new facilities in a way to limit GHG emissions [21].

The global community agreed during the Paris conference of 2015 to keep the global temperature at a maximum of 2°C above the preindustrial level [46]. The emission of greenhouse gases with carbon dioxide (CO₂) being the most dominant are directly responsible for global warming [47]. Carbon dioxide from fossil based combustion mainly in power plants is a significant contributor of the greenhouse gas emissions accounting for about 80% growth of emissions [48, 49]. This calls for maximum integration of renewable and low carbon sources which comes with significant challenges to the electricity grid. The stability of the grid is realized by line stability, voltage stability, and adequate control of reactive and active power with the objective of increasing and maximizing absorption from renewable energy sources. However large scale integration of renewables can lead to loss of synchronism, collapse of voltage, load shedding and significant deviation of system voltage and frequency which then leads to flicker, harmonics, high transmission and distribution losses, overloads and power oscillations which is highly undesirable and unsustainable [50]. Simultaneous reactive power management of transmission and distribution grid can maximize the renewable penetration at all layers of the grid.

The climate has been changing and consequences are being felt globally. Many developing countries including south Africa are facing the three challenges of grid electricity namely cost,

quality & reliability and environmental impact. The Paris Agreement set targets for all countries to reduce carbon emissions [48, 51]. Most of carbon emissions come from power plants of which 60% of global electricity comes from fossil fuel-based sources. Renewable sources like solar and wind which are significant face the challenge of intermittence and hence are unpredictable and unreliable. We must however use them as well as other renewables and low carbon sources to mitigate against carbon emissions and global warming while not compromising the cost, security and quality of grid electricity[52].

2.2 Methodology and Novelty of the Research

In this chapter, a transition to low-carbon energy future is examined with identification of potential options and strategies in line with broader sustainability goals and requirements. The study sought to identify conflicts and synergies between low-carbon strategies and the attainment of both short term and longer-term environmental, economic, technical, social, and institutional objectives. The research framework is organized across the five dimensions of sustainable energy and specifically electricity development which are environmental, economic dimensions, social aspects, technical dimensions, and institutional, political dimensions. The study adopted secondary method of data collection and analysis from recent primary and secondary data found in original research findings and reports from credible peer reviewed sources. This would facilitate the voice of the common people, professionals, experts, and authorities as well as governments for a cleaner global future. For this research, the term primary data refers to the data originated and carried out and presented as peer reviewed academic and professional papers and reports through personal interviews with the expert team or analysis based on primary data and presented as original reports or peer reviewed journal article. Therefore, this study is a review of the energy sustainable transitions globally. Published literature in the form of technical reports, peer reviewed journals and conference papers were reviewed by the authors. The study is a survey using credible literature from peer reviewed journals papers and energy data from various authorities globally. The main research output upon which this chapter is built on are references [2, 3].

Most studies on sustainable energy transition are narrow in scope as they tend to concentrate on the environmental dimension of sustainability. Researchers that look at sustainability more holistically also tend to concentrate on the three pillars of sustainability, namely economic,

environmental, and social dimensions of sustainability[141, 158, 159]. Past studies on energy transition also concentrate on energy sustainability in general. However, in this study, the focus is electricity as a secondary form of energy derived from primary sources of energy like wind, solar, hydro, nuclear, coal and gas through indirect conversion through a generator or direct conversion as in fuel cells and solar photovoltaics.

This study is unique as it looks at technical and institutional dimensions in addition to the economic, social, and environmental which are the main pillars of sustainable development. The study also brings into focus the role of the smart energy concept and other enablers of the transition in terms of technology and concepts like decentralization of generation, demand side management and behind the meter management measures. The study therefore recognizes that social foundations and human behaviors have a significant role to play in the future sustainability of the energy sector [146]. Therefore, the study pays attention and extensively analyses energy and electricity models and modelling tools that holistically considers sustainability in the energy sector and electricity systems.

2.3 Energy Related Emissions Energy Sustainability

The greatest sustainability challenge facing humanity today is the greenhouse gas emissions and the global climate change with fossil fuels led by coal, natural gas and oil contributing 61.3% of global electricity generation in the year 2020[3, 29, 160]. The energy-related CO₂ emissions have been rising year after year to reach 40.8 Gt of CO₂ equivalent (CO₂eq) in 2021 based on a 100-year global warming potential time horizon of which is a 6% increase from 2020 emissions of 36.3 gigatons (Gt). The energy combustion and industrial process contributed 89% of energy sector emissions for the same year, while gas flaring accounted for another 0.7%. Fugitive and combustion-related methane accounted for 10% of the total, and combustion-related emissions of nitrous contributed oxide 0.7%.[3, 160]. The energy sector methane emissions increased by about 5% in 2021 but remain below their 2019 level. As a result of the Covid-19 pandemic, energy demand in 2020 reduced leading to a reduction in global CO₂ emissions by 5.1%[160-162]. Global energy-related CO₂ emissions increased by 0.9% or 321 Mt in 2022, to reach a high of over 36.8 Gt. Whereas emissions from energy combustion increased by 423 Mt, emissions from industrial processes reduced by 102 Mt mainly due to production curtailments from China with and Europe, while a switch from gas-

to-coal playing a significant role in many countries due to unfavorable prices of natural gas. On the positive not in the emissions trend for the year 2022 was increased deployment of clean energy technologies like renewables, electric vehicles, and heat pumps which prevented 550 Mt in CO₂ emissions. Industrial production curtailment, particularly in China and Europe, also averted additional emissions. The transport sector emissions for 2022 increased by more than 250 Mt CO₂ to nearly 8 Gt CO₂, which was 3% more than the 2021 transport sector with aviation accounting for much of the increase, since air travel continued to rebound from pandemic lows to around 70% of 2019 levels[160, 163].

In demand recovered in 2021 mainly due to the adverse weather and energy market conditions, leading to more coal consumption even as the renewable power generation recorded the largest annual growth[3, 160]. The rebound in 2021 reversed the pandemic-induced emission reductions of about 1.9 Gt achieved in the year 2020. Compared to the pre-pandemic emissions of 2019, the 2021 emissions increased by 180 megatons (Mt) above [161]. The 6% increase the 2021 emissions was in line with the global economic output growth of 5.9%. This indicates a strong coupling of CO₂ emissions with Gross domestic product (GDP) growth since 2010, that realized a global emissions rebound of 6.2% compared with economic growth of 5.1% when the world emerged from the Global Financial Crisis[161, 162].

The majority of global anthropogenic emissions are derived from the energy sector, contributing to 72.0% of global emissions with most of the energy going to toward heat and power production which is about 31%, followed by agriculture (11%), transportation (15%), forestry (6%) and manufacturing (12%). The main greenhouse gas emissions are , carbon dioxide, which is the largest accounting for about 76%, followed by methane at about 16% , and nitrous oxide accounting for about 6% of global greenhouse gas emissions[3, 50]. The challenge facing the energy sector in continued reliance on fossil fuels mainly in form of coal, natural gas, and oil[93].

Carbon footprint refers to the total greenhouse gas emissions caused by an organization, a community, event, service, product, or a country. Greenhouse gases are gases that absorb and emits thermal radiation, leading to a “greenhouse effect” near the Earth’s surface and ultimately warms the planet[35]. Although the Earth needs the greenhouse effect to keep it

habitable, the overabundance of greenhouse gases in atmosphere disrupts the Earth's carbon cycle and accelerate global warming which is the scenario unfolding today[93, 164]. Fossil fuels are the main contributors of greenhouse gases led by carbon dioxide. The carbon footprint is usually expressed as units of CO₂—typically metric tons (1,000 kg/2,205 lb = 1 t), million tons (1,000,000 t = 1 Mt) or gigatons (1 billion metric tons/1,000 Mt = 1 GT[29, 50].

2.4 Greenhouse Gas Emissions by Economic Sector

Greenhouse gas emissions can generally be divided into five global economic sectors by source i.e. energy supply; manufacturing industry; agriculture, forestry and other land-use change (AFOLU); transport; and direct energy use in buildings. The energy sector has realised the greatest growth in greenhouse gas emissions since 1990, for applications in industry, transport and power generation. The energy sector contributed 20 GtCO₂e (37 per cent of the total) in 2020, followed by industry which contributed 14 GtCO₂e (26 per cent), AFOLU was 9.5 GtCO₂e (18 per cent), transport 7.6 GtCO₂e (14 per cent) and buildings was 3.1 GtCO₂e (5.7 per cent). [165]

The various economic sectors have varying degrees of environmental impact in terms of emissions as well as mitigation strategies as follows;

i. Electricity and Heat Production

About 25% of the anthropogenic greenhouse gas emissions came from electricity and heat production which include coal combustion, natural gas, and oil combustion for electricity and heat application. This constitutes the highest single source of global greenhouse gas emissions [166]. This percentage can be reduced through options like cogeneration for own power generation, shift to renewable energy sources and energy generation and conservation efficiency[12, 58, 61].

ii. Industry

About 21% global greenhouse gas emissions come from industrial operations with onsite facilities for energy production mostly involving fossil fuels like coal, gas, and petroleum products like diesel. These sources include industrial chemical processes, metallurgical processes, and mineral refining and transformation processes[166]. The industrial sector is also characterized by huge and diversified consumption of energy resources. The industrial sector also has the most diversified application of energy[167]. This makes the industrial sector a

candidate of wide-ranging energy saving energy options. Methods that can be applied include process efficiency improvement, cogeneration and use of renewable and alternative sources can significantly reduce greenhouse gas emissions from industrial processes. Therefore, industry has a very important role to play in the energy transition to green and low carbon energy sources[3].

iii. Agriculture, Forestry, and Other Land Use

Emissions from agriculture, forestry, and other land applications account for about 24% of global greenhouse gas emissions. Agricultural activities like crop cultivation, livestock farming activities and agricultural related deforestation, although the value does not include carbon dioxide removed from the atmosphere by sequestering carbon in biomass through the natural process of photosynthesis which offsets about 20% of carbon dioxide emissions from the atmosphere[166]. This shows the positive side of agricultural activities which can be enhanced through agroforestry, and energy crops farming which help reduce atmospheric CO₂ concentrations. This implies that the use of energy crops and biomass sources for power generation has a significant role in the transition of energy and grid power generation to low carbon and green electricity[3].

iv. Transportation

The transport sector is one of the leading polluters contributing 14% of 2010 global greenhouse gas emissions. The main sources are transportation activities on road, rail, air, and marine transportation. About 95% of the 14% emissions from transportation energy sector comes from petroleum-based fuels, in form of petrol, gasoline and diesel[166]. Additionally, the transportation sector heavily relies on petroleum-based fuels with light duty vehicles being the dominant users of the fuel consumed in transportation[167]. Measures to limit these emissions include use of electricity from renewable sources in traction e.g., rail, increased use of biofuels and other renewable energy fuels and investment in fuel efficiency measures. Therefore, electrification of transport promise to have a huge impact on carbon emissions mitigation if grid electricity is derived from renewable and low carbon electricity sources like nuclear and renewable sources like wind, solar, geothermal[12, 61].

v. Buildings

The building sector is another source of emissions accounting for about 6% of the global greenhouse gas emissions. Main building sector activities responsible include onsite power

generation, burning fuels for heat in buildings, or cooking and other energy consuming activities[166]. On the positive side buildings can significantly reduce this load by own generation from renewable sources, energy savings and decentralized grid generation for grid supply. Buildings are the largest consumer of electricity and additionally they are the largest consumer of primary energy[167]. Therefore, promotion of renewable energy sources is a solution to these emissions especially through decentralized generation from renewable sources aimed at reducing the load on electricity grids [167].The contribute to energy transition to a green and a low carbon grid electricity by increased use of decentralized generation from renewable sources like geothermal wellhead, wind, solar and hydropower generation[58, 168, 169]. The use of smart grids can significantly enhance onsite grid connected power generation from intermittent renewables[3].

vi. Other Energy

The remaining 10% of global energy demand comes from energy sector related sources other than heat and electricity production like fuel extraction, extraction and refining, processing, and stationary automotive engine applications[166]. Energy economics and efficiency applications in consumption and use of renewable energy sources can reduce this type of emissions[3].

The global greenhouse gas emissions can also be broken down by the economic activities that lead to their production. These activities contributing greenhouse gases include other energy, related sources, and industry, transportation, buildings then agriculture and forestry activities. The greenhouse gas emissions by sector is presented in Figure 2-2.

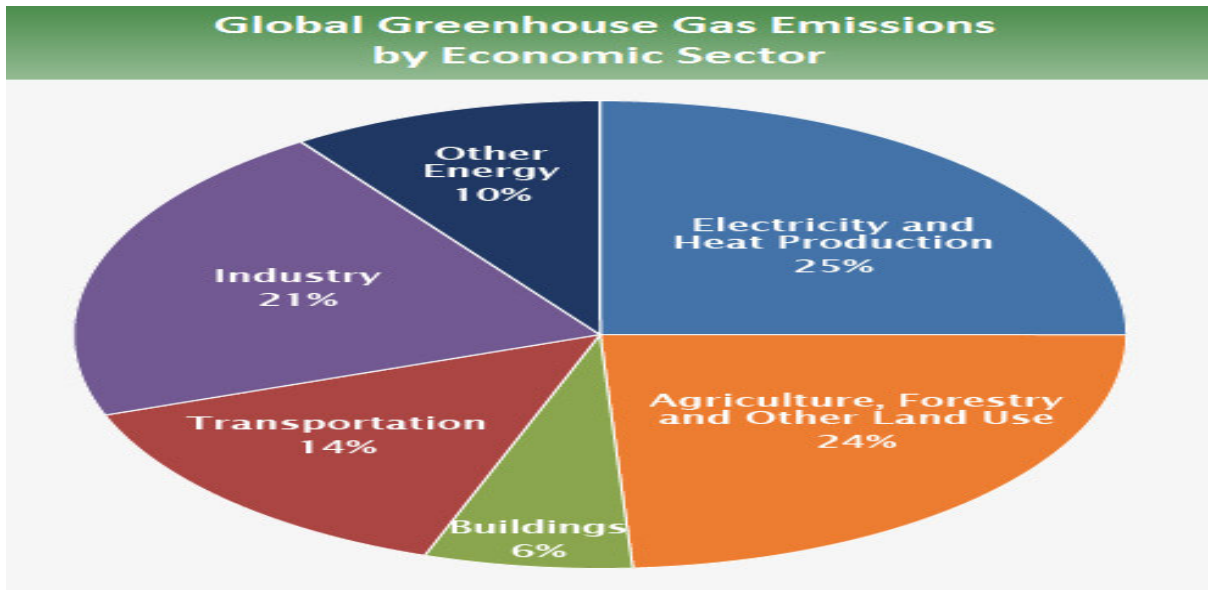


Figure 2-2: Greenhouse gas contribution by economic sector [170]

From Figure 2-2, it is noted that electricity and heat generation account for 25% of emissions while other energy accounts for 10%, while transportation accounted for 14% of the global greenhouse gas emissions.

De-carbonization of grid electricity is a leading option in the effort to minimize greenhouse gas emission and related consequence of climate change. However, for grid electricity decarbonization, there must be increased penetration of renewable sources particularly the intermittent wind and solar. Increased penetration of these sources will increase grid instability [50].

The focus of this study is to investigate the added value of the inclusion of technical, economic, and social parameters in electrical power generation systems in an energy system model with high levels of variable renewable generation sources in a mix with low carbon sources and fossil fuel sources. The motivation for the work is to ascertain whether the modelling of the electrical power system within the energy system model is capable of correctly capturing and including the effects of variability, carbon value and cost of energy sources on the power system with the objective of minimising both price and carbon emissions.

Electric power systems are generally designed on the principle of power production in central power stations with electricity delivery to end user through transmission and distribution networks. The traditional system consists of Generation from various energy sources, Transmission via high voltage network and Distribution to consumer at medium and low voltage network. Therefore, the role of transmission is to act as the interface between generation and distribution functions usually over long distances to realise economic and system like reduced power losses and cost to realise high system efficiency. The role of distribution is to act as the interface between transmission and end users via electrical distribution delivery infrastructure[171].

2.5 Specific Greenhouse Gas Emissions

At the global scale, the key greenhouse gases emitted by human activities are:

2.5.1 Carbon Dioxide (CO₂)

Carbon dioxide (CO₂) is a greenhouse gas with the ability to absorb and radiate thermal energy. The Natural increases in CO₂ concentrations have been warming the earth over time with increase in temperature during ice age cycles over millions of years. These warm episodes or interglacial started with a small increase in sunlight when the earth had a tiny wobble in its axis of rotation around the Sun. This event led to some warming of the earth's surface and oceans causing increased release of carbon dioxide. The extra CO₂ in the atmosphere magnified the initial warming. Among the anthropogenic greenhouse gases, CO₂ is responsible for about 60% of the greenhouse gas effect[172].

The use of fossil fuels like coal, natural gas, and petroleum (diesel and petrol) is the primary source of CO₂ emissions especially in power generation. Other leading sources are direct human-induced operations and activities like deforestation for land preparations, charcoal burning and human settlements. According to carbon dioxide enters the atmosphere from combustion of fossil, solid waste, vegetative matter, and other biological materials[8]. Other leading sources are industrial chemical reactions like cement production. Carbon dioxide is mainly removed from the atmosphere or sequestered through photosynthesis [173]. Carbon dioxide absorbs and radiates heat and so when warmed by sunlight, it continuously radiates heat in form of thermal infrared energy. Without this radiation, the earth's average annual temperature would be just close to 60°F. With the rapid increase in greenhouse gas emission,

additional heat has been trapped leading to raising Earth's average temperature above the pre-industrial level[3, 29].

2.5.2 Methane (CH₄)

Agricultural activities, waste management, energy use, and biomass burning all contribute to Methane emissions. Methane generated from various natural and artificial processes like anaerobic digestion and during the production and transport of fossil fuels like coal, natural gas, and oil. [173]. Therefore, methane is added to the atmosphere through natural and anthropogenic sources. 30% of the methane flux originates from natural sources while about 70% is contributed by anthropogenic sources. Natural sources contribute approximately 160 Tg (CH₄) yr⁻¹ (1Tg= 10¹² g, 1000 Tg = 1Gt). Wetlands, termites, and oceans are the largest natural sources contributing about 115, 20, and 10 Tg (CH₄) per year, respectively [174]. Controlled biodegradation through anaerobic digestion and use of clean fuels is the best strategy to limit methane emissions.

2.5.3 Nitrous Oxide (N₂O)

Food production particularly the use of fertilizers is the primary source of N₂O emissions. As well as fossil fuel combustion in power generation, industry, and transportation as a product of combustion and wastewater treatment process (EPA, 2017). Nitrous oxide (N₂O) is the third most abundant well mixed greenhouse gas after CO₂ and CH₄ a life span of about 130 years. The natural sources of N₂O come from soils and the oceans and are estimated to deliver 10.2 TgN yr⁻¹ to the atmosphere. Anthropogenic emissions originate from biomass combustion, fossil fuel combustion, and industrial production of adipic and nitric acids, and nitrogen fertilizer use in agriculture[174]. Measures to limit Nitrous oxide (N₂O) emissions include use of cleaner and renewable fuels, controlled combustion of fuels and exhaust gas cleaning measures among others.

2.5.4 F Gases

The F gases result from industrial processes, refrigeration systems, and the use of some consumer products associated with emissions of F-gases. These gases include hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆). Hydro fluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride are synthetic, and come from industrial processes. These Fluorinated gases are occasionally used a substitute

for ozone-depleting substances e.g., chlorofluorocarbons, hydro chlorofluorocarbons, and halons. These gases have high global warming potential gases even though they are released in small quantities[173]. The main negative impact of Sulphur hexafluoride (SF_6) is that is highly potent and has intense absorption at $10.3 \mu\text{m}$ (969 cm^{-1}) in the atmospheric window region and while it has atmospheric lifetime of 3200 years. SF_6 is present in small amounts in fluorites which provides a small natural source that results in a natural background concentration of 0.01 ppt. The gas is a useful industrial chemical used as an insulating gas in electrical switching equipment. Anthropogenic emissions have increased the level of SF_6 in the atmosphere to approximately 400 times more than natural background levels and the concentration increases at about 0.2 ppt yr^{-1} . Another related gas SF_5CF_3 . Its level in the atmosphere increased from zero in 1960 to 0.12 ppt in 1999. Although the concentration of SF_5CF_3 is very low and with insignificant role in global warming, it is of major concern since it is the most potent greenhouse gas yet identified on a per molecule basis in the atmosphere[174].

The relative composition of atmospheric greenhouse gases emissions is summarized sized in Figure 2-3.

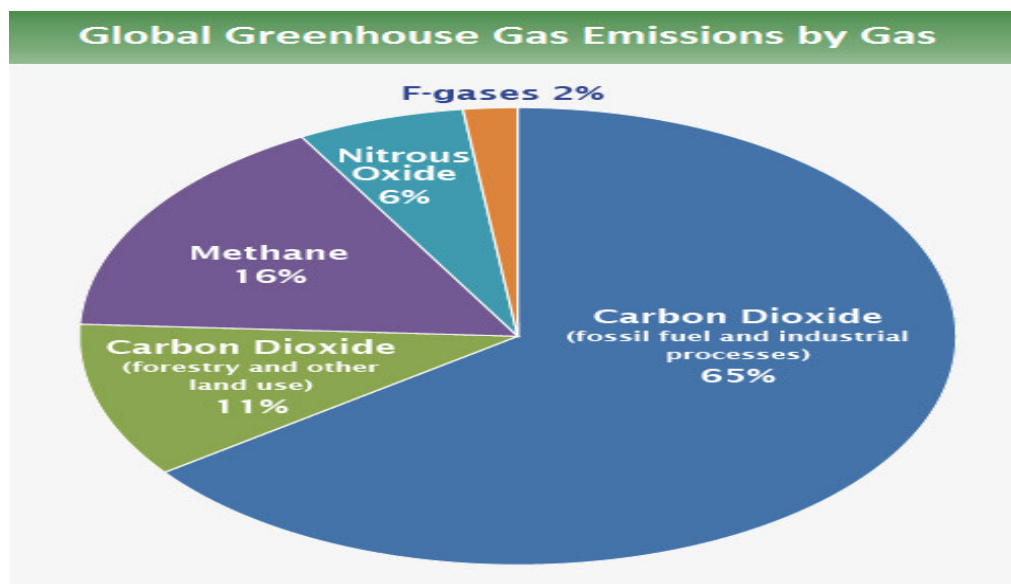


Figure 2-3: Global greenhouse gas emissions by gas[166].

From Figure 2-3, it is noted that carbon dioxide remains the dominant greenhouse gas with most of it coming from fossil fuel combustion in industry, heat, and power generation. Other sources of carbon dioxide are agriculture and forestry related activities.

2.6 Energy Emissions Intensity

The global primary energy intensity is a very important indicator of how the world's economic activity consumes energy improved. Emerging economies in Central, Southern, Eastern and South-eastern Asia continue to experience increased economic activity but energy consumption rise is mitigated by increases energy efficiency, leading to a robust, continuous improvements in energy intensity[175]. Energy intensity increased by 3.1. % in South-eastern Asia, 0.8% for Western Asia, Northern Africa, Latin America, and the Caribbean and 1.4. % for Sub-Saharan Africa between 2010 and 2018. These rates of energy intensity reduced compared with the period 1990–2010 for all sectors except the transportation sector where fuel efficiency standards drove energy intensity improvements[175].

Emissions intensity in power generation is measured in kg CO₂-equivalents (CO₂eq)/MWh). It is used to compare the specific greenhouse gas (GHG) emissions of mitigation strategies for emissions and emissions from conventional power generation technologies. On the other hand Levelized cost of energy (LCOE) which is measured in USD2010/MWh is used to compare the generation costs for various power conversion technologies [176].

The emission intensity of electricity generation is used to compare the specific greenhouse gas (GHG) emissions of suggested emission mitigation options and those of conventional power supply technologies. The emissions intensity is measured in kg CO₂-equivalents (CO₂eq) / Wh) [177]. An emission intensity which is also referred to as carbon intensity or C.I refers to the emission rate source relative to the intensity of a specific activity, or process e.g. grams of carbon dioxide produced per kW of energy produced, or the ratio of emissions generated to the gross domestic product (GDP). Emission intensities are applied to derive values of pollutant or greenhouse gas emissions on the basis fuel consumed, animals in animal husbandry, level of industrial output, distance travelled and other similar activity data. Emission intensities of sources can also be used to in comparing the environmental impact of various energy sources and technologies. The emission factor and carbon intensity are other terms used interchangeably for different fields/industrial sectors. The term, "carbon" when used usually excludes other pollutants, like particulate emissions. Commonly used value is the

carbon intensity per kilowatt-hour (CIPK), which is used to compare emissions from different sources of electricity[162, 178].

Energy intensity is often used to assess the energy efficiency of a particular economy. The numerical value for energy intensity is traditionally computed by taking the ratio of energy use (or energy supply) to gross domestic product (GDP), indicating how and it shows how well the economy converts energy into monetary output while typical units for energy intensity are joules (or Btu) per US dollar; although we have other equivalent metrics used. A small energy intensity ratio is, depicts lower energy intensity for the country with lower energy intensity being desirable. Effort to decouple energy use and economic output is required to enhance that quality[179, 180].

During the initial stages of development, energy intensity normally increases, while GDP and energy are coupled closely in the initial development stages of a nation, mainly because of early years of access and use of modern energy which is more abundant like fuels and electricity as the need to produce more cement for roads and buildings emerges and steel for automobiles, appliances, and telecommunication infrastructures as new uses, of which some are energy intensive. Once development has taken place, and industries are established, the energy intensity starts falling as effects of cost-cutting is employed to “squeeze” more value out of now established markets and manufacturing subsectors[180].

Energy intensity may be reduced by several means like application of energy efficient extraction and conversion techniques, increasing production efficiency and allowing other countries to produce the manufactured products and purchase them which increased GDP via similar or greater product output/usage for the same or lower energy usage, which subsequently reduces the energy intensity. There is a trend of reducing energy intensities of economies in the latter half of the 20th century, which will continue to grow as a result of increased efficiency and expansion of activities that yield value for intrinsically less energy input like how primary energy consumption and gross domestic product (GDP) change over time globally relative to a normalized year 1971 when the energy crisis started[179, 180].

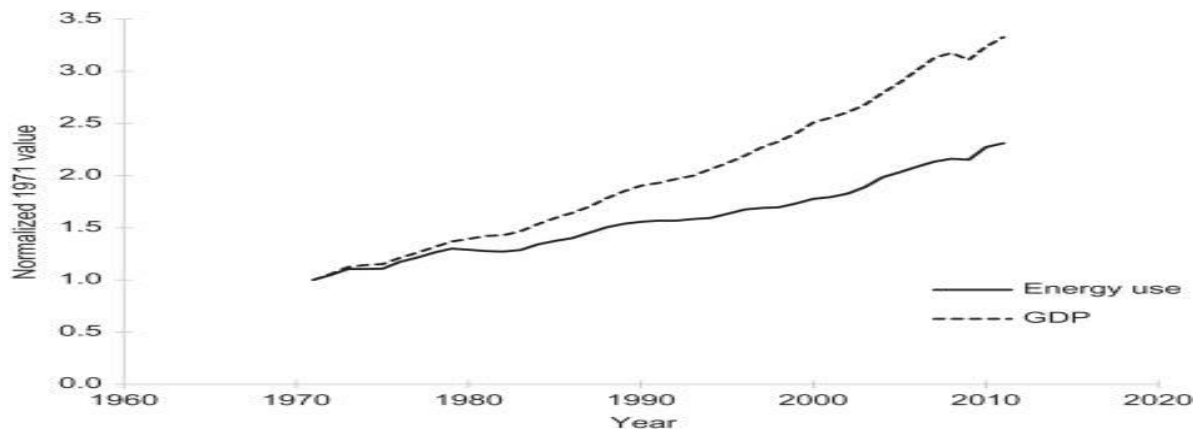


Figure 2-4: World energy use and GDP changes from 1971 to 2011

From Figure 2-4, it is noted that World energy use and GDP changes from 1971 to 2011, normalized to 1971 values. The decoupling of energy use and GDP steadily increases where intensity reduces with time Gross domestic product.

Despite the obvious reduction in global energy intensity, it is important to consider individual, national trends, because many affluent nations reduce their industrial activity, and shift to activities that are less energy intensive which is tantamount to exporting the industrial activity to other industrializing nations. Several economies have shifted toward more manufacturing, which carries with it more energy consumption, and tighter coupling. The “export” of manufacturing to less affluent nations is a shift toward less efficient operations.

The diminishing energy intensity is well established and will continue but can be expected to level out substantially mainly because first is existence of a saturation point in many trends, since energy conversions are limited and the transition to intrinsically less energy intensive economic activities can only go so far. As the economy grows and manufacturing expands, there is need for replacement of existing devices, development of new homes and facilities, transportation, communication infrastructure, entertainment and other services which all require energy.

2.7 Energy Efficiency and Conservation

Energy efficiency and conservation have a role to play in achieving global emissions and climate change proposed in the Paris agreement and other protocols. Conservation and efficiency measures facilitate reduction in greenhouse gas emissions, reduce fuel consumption, reduce load and strain on the grid, and cost reduction in both generation and

cost of electricity consumed[181]. The main challenge facing adoption of efficiency and conservation measures is lack of appropriate technology and high capital requirements which creates financial management risk and undetermined return-on-investment and hence undetermined payback periods that significantly limit their adoption[181]. Significant amounts of energy in many forms including heat, electricity and even primary resource are lost or wasted through transmission, heat loss and application of inefficient technology. This is a huge cost to consumers who must pay for the lost energy. Additionally, more energy is consumed to cater for the losses which effectively leads to more pollution for every extra unit consumed to compensate for the losses[182]. Therefore, putting in place various energy efficiency measures is one of the easiest and cost-effective means of combatting climate change, limit emissions and related pollution, reduce energy costs and improve the competitiveness of businesses[182]. In a sustainable energy scenario by the International Energy Agency, energy efficiency is expected to deliver more than 40% of targeted reduction in energy-related greenhouse gas emissions between 2020 and 2040 as a strategy to put the world on track to achieve international emissions and related climate change targets[181, 183]. Therefore, energy efficiency and conservation measures have a very important role to play in the sustainable energy transition.

2.8 Global Warming

Global warming is a phenomenon that occurs when CO₂ and other air pollutants absorb sunlight and solar radiation in the atmosphere, resulting in trapping the heat to and act as an insulator for the planet earth. Between 1880 and 1980 the average global temperature increases by 0.07 C every 10 years, but has more than doubled since 1981, rising to global annual temperature rise of 0.18C, or 0.32F, for every 10 years. [184]. The climate change is arguably the most severe, long-term, global impact of fossil fuel combustion. The carbon in fossil fuels and biomass material forms CO₂ in combustion and forms a heat blanket leading to the warming of the earth [184].

Climate change is the long-term shift in global average temperatures and weather patterns which can be due to changes in the sun's activity or can be a result of large volcanic eruptions which are natural in nature. However, as from the 1800s, man and his activities have become the main driver of climate change, primarily as a result of fossil fuels combustion which

generates greenhouse gases which act as a blanket wrapped around the Earth, leading to the trapping of sun's heat and raise in temperatures. The main greenhouse gases include methane and carbon dioxide originating from multiple sources like land clearing, biomass decomposition, and deforestation. Major sectors contributing to the greenhouse gases are agriculture, oil, and gas operations. The main sectors contributing the greenhouse gases are energy, industry, transport, buildings, agriculture and land use are among the [185].

It has been shown by Climate scientists that human beings are the cause for virtually all global heating over the last 200 years which has caused the temperature of the Earth's surface to rise by 1.1°C above the pre- industrial revolution temperature which is warmer than at any time in the last 100,000 years. Since it is the Earth is a system where everything is connected, changes in once area triggers changes others. [185].

2.8.1 Climate Change and Causes

The largest the largest contributor to global climate change, accounting for over 75 per cent of global greenhouse gas emissions and nearly 90 per cent of all carbon dioxide emissions is fossil fuel combustion. The greenhouse gases emitted blanket the Earth leading to trapping of the heat from the sun leading to global warming and climate change. Global warming is currently a serious concern because the earth is now warming faster than at any point in recorded history. This warming is changing the weather patterns leading to disruptions to the usual balance of nature thus endangering human beings and all other forms of life on Earth. As well as their environment [160, 185].

i. Generating Power

Fossil fuel based power generation accounts for a significant proportion of global emissions with close to 60% of global electricity being generated by burning coal, oil, or gas, producing carbon dioxide and nitrous oxide and sulphur dioxide which are powerful greenhouse gases. [185].

ii. Manufacturing Goods

The manufacturing sector generates emissions mostly from burning fossil fuels for energy in processes like cement, iron, steel, electronics, plastics, clothes, and other goods. Industrial processes also release other greenhouse gases like NO_x, SO₂ making the manufacturing industry one of the largest contributors to greenhouse gas emissions globally [160, 185].

iii. Deforestation

Deforestation and agriculture accounts for out a quarter of greenhouse gas emissions globally. The main reasons for deforestation include creation of pasture, or for other reasons, which leads to destruction of trees. About 12 million hectares of forest are destroyed annually which leads to release the carbon stored. Since forests absorb carbon dioxide, there destruction limits nature's ability to remove carbon dioxide emissions out of the atmosphere. [185].

iv. Transportation

Most transport vehicles including cars, trucks, ships, and planes are powered by fossil fuel. making transportation a major emitter of greenhouse gases with road vehicles accounting for the largest part, from use of petroleum-based products, diesel, and petrol, in internal combustion engines. The transport sector accounts for close to one quarter of global energy-related carbon-dioxide emissions [35, 185].

v. Powering Buildings

The residential, and commercial buildings account for more than 50% of electricity consumption even as they additionally continue to draw on coal, oil, and natural gas in applications like heating and cooling, leading to significant quantities of greenhouse gas emissions. Growing energy demand for heating and cooling, with rising air-conditioner ownership and use have contributed to growing electricity demand for appliances, lighting, and connected devices, contributing to a rise in energy-related carbon-dioxide emissions from buildings in recent years.

vi. Inefficient Use of Resources and Consumer Choices

The choice of what you use, how you use energy, what you consume and how you move around as well as how much waste you generate and how much you throw away contribute to greenhouse gas emissions. A significant amount of global greenhouse gas emissions is linked to inefficient use of resources and non-optimal choice of resources by private households and organizations. Therefore, our lifestyles have a profound on the planet earth and its environment. [162, 185].

vii. Food Production

Food production increases emissions of carbon dioxide, methane, and other greenhouse gases through deforestation, and clearing of land for agriculture and grazing, digestion by like cows

and sheep, fertilizer production and use, and the use of energy by farm equipment that use fossil fuels, as well as packaging and distribution of food [32, 185, 186].

2.8.2 Consequences of Climate Change

There are many consequences of climate change like intense droughts, water scarcity, flooding, severe fires, rising sea levels, polar ice melting, catastrophic storms and decline in biodiversity[185]. Climate change has effects on health, agriculture, housing, safety, and work. People living on small island nations and other developing countries are particularly vulnerable to climate change because of conditions like sea-level rise and saltwater intrusion which can force communities to relocate, famine due to protracted droughts and diseases [16, 185].

i. Higher Temperatures

Studies show that since the 1980s, each successive decade has been warmer than the previous one and nearly all land areas are experiencing hot days and heat waves. Heat related illnesses are associated with higher temperatures and making working outdoors more difficult. While wildfires start and spread easily and more rapidly when it is hotter. The temperatures in the Arctic have increased at least twice as fast as the global average[185]., and today Earth's atmosphere is 1.5°C warmer compared to 1880. Although this temperature rise seem like not too hot, the rise creates regional and seasonal temperature extremes, reduce sea ice, intensify rainfall and drought severity, and change habitat ranges for plants and animals.[184]

ii. More Severe Storms

Climate change will cause more intense and more frequent destructive storms in many regions. Temperature rise increases, evaporation of moisture, which exacerbates extreme rainfall and flooding, that cause more destructive storms. The ocean warming also increases the frequency and extent of tropical. Hurricanes, Cyclones, and typhoons feed on warm waters at the surface of the ocean. The storms have impacts like home destruction, death and huge economic losses[185]. Storm-affected experience significant rise in precipitation and flooding while areas located further from storm tracks realise decrease amount of precipitation and droughts[184]

iii. Increased Drought

Climate change is altering the availability of water, making it scarcer in many geographical regions. Global warming exacerbates the shortage of water in already water-stressed regions leading to increased risk of agricultural droughts affecting crops, Drought increases the vulnerability of ecosystems and can lead to destructive sand and dust storms that can move billions of tons of sand across continents. Desertification due to drought is reducing arable land and hence food insecurity and poverty and lack of water and poor sanitation [185]. Whereas storm-affected areas experience higher precipitation and flooding, several areas that are far from the storm tracks are affected by precipitation and droughts[184]

iv. Rise in Sea Level

The ocean absorbs most of the heat from global warming hence global warming has increased ocean warming over the past two decades, across all depths of the ocean leading to its volume increases since water expands as it gets warmer. Additionally, the melting ice sheets contributes to sea levels rising, threatening coastal and island communities. The ocean also absorbs carbon dioxide, but more carbon dioxide makes the ocean more acidic, which endangers marine life and coral reefs [185]. The global Sea levels have increased by about 8-9 inches since 1880, causing displacement of people along coastlines and destroying coastal habitats. The costal infrastructure is threatened by the rise in sea level resulting from the melting of polar ice because of global warming. These infrastructure include roads, water supplies, bridges, subways, oil and gas wells, power plants, waste water treatment plants, and landfills [184]. Notable evidence is the decline in arctic sea ice by 30% since 1979. The ice sea plays an important role in regulating the earth's climate by reflecting sunlight into space and to provide a habitable environment for plants and animal species. The sea level will rise by approximately 70 feet if all the ice melts which will effectively flood out every coastal city on the planet[3, 184]

v. Hunger and Starvation

Climate change and increases in extreme weather incidents are leading causes of global rise in hunger and poor nutrition since crops, fisheries, and livestock are destroyed or become less productive. Ocean acidification, places marine resources that feed billions of people are at risk while changes in snow and ice cover in many Arctic regions have led to disruptions in food supplies. Heat stress diminishes grasslands and water ability to sustain for grazing, causing decline in livestock and crop production yields [185].

vi. More Health Risks.

Climate change is a serious health threat facing humanity with climate impacts already harming health, through diseases, through air pollution, extreme weather events, pressure on mental health, forced displacement, and increased hunger and poor nutrition where people cannot grow food or find sufficient food. Environmental factors take the lives of around 13 million people annually. Extreme weather events lead to increased deaths, as weather patterns expand diseases, and make it difficult for health care systems to contain them [185].

vii. Poverty and Displacement

Climate change increases phenomena that keep people in poverty like flooding which may sweep away urban slums, destroying homes and people's livelihoods. High temperatures make it hard to work in outdoor jobs, while water scarcity due to drought affects agriculture. Between 2010–2019, weather-related events led to displacement of close to 23.1 million people on average annually, leaving many more vulnerable to poverty, with most refugees coming from countries that are most vulnerable and least prepared to adapt to the impacts of climate change [185].

viii. Loss of Species

Climate change poses risks to the very survival of several species on land and water. These risks increase as temperatures climb. The world is losing species at a rate 1,000 times greater than it did at any other time in recorded human history with close to one million species being at the risk of becoming extinct within the next few decades. The threats to the species include wildfires, extreme weather conditions, invasive pests and diseases which are all related to climate change. Although some species will relocate and survive while a few will adapt, others will not. [185].

ix. Ocean Acidification

The PH of the ocean has increased by 0.1 pH units over the last 200 years which translates to a 30% increase in ocean acidity. About 30% of the CO₂ released into the atmosphere, is absorbed by the ocean which leads to a reduction in the pH (increases the acidity) of the ocean. This acidification disturbs aquatic life leading to death and disappearance of some species and other environmental impacts like the coral bleaching, where coral expel the algae (zooxanthellae) that live in their tissues as a result of changes in temperature, light, or nutrients.[184]

2.8.3 Global Strategies to Reduce Carbon Footprint.

According to experts, to avoid a future plagued by challenges like rising sea levels, acidified oceans, loss of biodiversity, more frequent and severe weather events, and other environmental disasters caused by the climate change, global warming to 1.5 °C by 2040. Reducing CO₂ emissions, slows down the rate of the rate of temperature rise, rise in sea-level rise, melting of polar ice, and ocean acidification leading to ability of the earth's biodiversity to adapt to the changes [2, 184].

Various UN reports, and thousands of scientists and government reviewers have generally agreed that it is necessary to limit global temperature rise to no more than 1.5°C above the preindustrial level to maintain a livable climate and avoid the worst climate impacts. A Business as Usual scenario based on policies currently in place will generate a temperature rise of about 2.8°C by the end of the century. The seven biggest emitters alone i.e., China, the United States of America, India, the European Union, Indonesia, the Russian Federation, and Brazil jointly accounted for close to half of all global greenhouse gas emissions in 2020, yet the consequences affect all nations[16, 185]. Many climate change measures also lead to economic benefits thus improving lives and protecting the environment simultaneously. There are global agreements and frameworks that guide sustainability and environment management like the Sustainable Development Goals, the Kyoto protocol (UN Framework Convention on Climate Change), and the Paris Agreement. The three broad categories of action are:

- i. Reduce emissions,
- ii. Adapt to climate change impacts, and
- iii. Finance the adjustments required.

An important strategy in cutting down emissions is a switch of energy systems from fossil fuels to renewable energy sources. Many countries are committed to net zero emissions by 2050, but for the warming to be below 1.5°C, the emissions should be cut by half by 2030 which requires a huge decline in fossil fuel consumptions. By adapting to climate consequences helps to protect people, their homes, livelihoods, businesses, the infrastructure, and natural ecosystems by addressing current and future impacts. Adaptation must be

prioritized for the most vulnerable in society to cope with climate hazards. Measures include early warning systems for disasters. Climate action requires significant financial investments. But taking no inaction is vastly more expensive [185].

Developed countries have higher carbon footprints and higher CO₂ emissions because they have more robust energy industries, burning huge quantities of fossil fuels to provide power, and a larger proportion of the people own their own automobiles which emit carbon emissions. Methods applied to reduce the carbon footprint include generating electricity from renewable energy sources, instead of fossil fuels, higher energy efficiency, use of biofuels in transportation, reducing automotive emissions, recovery greenhouse gases like methane from landfills and smokestacks, penalties and taxes like a carbon tax on emitters, and reversing deforestation[82]. Many countries have pledged to apply different measures to become carbon neutral, and a few countries have managed to become carbon negative countries. At individual level, measures to reduce carbon footprint include walking and biking to work, use public transportation instead of driving, use of containers, reduce power consumption and eating less red meat[39].

The areas that need to focus on in the effort to reduce emissions are electricity, heat, transport, and industrial activities and food and agriculture. Appropriate measures can be summarized by two core concepts: efficiency improvement to ensure use of less energy for a given output level and using less land, fertilizer, and other inputs for food production, and reducing food waste); and use of low-carbon energy sources like renewables and nuclear[16, 39].

Several measures should be put in place to ensure that energy systems promote sustainable development. The main challenges are expanding access to affordable, reliable, and adequate energy supplies while addressing environmental impacts at all levels. Policies can support sustainable development by:

- i. Delivering adequate and affordable energy supplies including liquid and gaseous fuels for cooking and electricity for domestic and commercial use to unserved areas.
- ii. Encouraging energy efficiency.
- iii. Accelerating the use of new renewables.
- iv. Widening the diffusion and use of other advanced energy technologies

2.8.3.1 Kyoto Protocol

The Kyoto Protocol which was adopted in Kyoto, Japan, on December 11, 1997, and entered into force on February 16, 2005, was an important first step toward a global emission reduction system aimed at stabilising GHG emissions. It provided the architecture to guide future international agreement on emissions and climate change[187]. The agreement is linked to the United Nations Framework Convention on Climate Change, that commits its Parties by through setting internationally binding emission reduction targets. The Protocol places a heavier burden on the industrialized and developed countries under the principle of “common but differentiated responsibilities by recognizing that the developed countries are principally responsible for the bulk of the greenhouse gas emissions over the more than 150 years of industrial activity. The Kyoto protocols detailed rules for the implementation were adopted at COP 7 in Marrakesh, Morocco, in 2001, and hence referred to as “Marrakesh Accords.” With first commitment period starting in 2008 and ended in 2012[187].

The industrialized countries were committed to reducing emissions of six gases that cause global warming in the period between period 2008–12 by 5% based on the 1990 emission levels. The European member states committed to reduce their emissions by 8% during this period[187].

The Kyoto protocol was amended in Doha, Qatar, on December 8, 2012, the Kyoto to include the following items:

- i. New commitments covering the period 2013–20.
- ii. An updated list of greenhouse gas emissions (GHGs) to be reported in the period of the second commitment and
- iii. Some amendments several articles of the Kyoto Protocol that required to be updated for the period of the 2nd commitment.

In this 2nd commitment, the parties to the Kyoto protocol committed to reduce the GHG emissions by at least 18% below 1990 emission levels over the 8-year period from 2013 to 2020. The composition of Parties to the Kyoto protocol in the second commitment period is different from the first one.

The Kyoto Protocol offered three market-based mechanisms for the Parties to realize the emissions targets. These mechanisms are:

i. International Emissions Trading.

Emissions trading was set out in Article 17 of the Kyoto Protocol, and allowed countries that have emission units permitted but not used to sell the excess capacity to countries that exceeded their targets, thus creating a new energy commodity of exchange in the form of emission reductions or removals. Often referred to as trading in carbon in which the emissions are tracked and traded like any other commodity in what is referred to as the. “Carbon market”.

ii. Clean Development Mechanism.

The clean development mechanism, as defined in Article 12 of the Kyoto Protocol, which allowed countries having emission-reduction or emission-limitation commitment under the Kyoto Protocol to execute an emission-reduction project in developing countries to earn them saleable certified emission reduction credits. One emission credit is equivalent to 1 ton of carbon dioxide, and is used towards achieving the Kyoto targets[187].

iii. Joint Implementation.

Article 6 of the Kyoto Protocol defines the joint implementation mechanism which allows a country with an emission reduction or limitation commitment under the Kyoto Protocol to earn emission reduction units obtained from an emission-reduction or emission-removal project in another Party. Each unit is equivalent to 1 ton of carbon dioxide, that is counted toward achieving the country’s emissions target [187].

2.8.3.2 Paris Agreement and Implications on Energy and Power Generation

The Paris Agreement which is often referred to as the Paris Accords or the Paris Climate Accords, is an international treaty on the climate change that was adopted in the year 2015 covering climate change mitigation, adaptation, and finance. This agreement was negotiated by 196 parties at the 2015 United Nations Climate Change Conference near Paris, France. The agreement was opened for signature on 22 April 2016 (Earth Day) at a ceremony that was held inside the United Nations Headquarters in New York. By February 2023, 195 member states of the United Nations Framework Convention on Climate Change (UNFCCC) had

ratified the agreement, with the US withdrawing in 2020 but rejoined in 2021, while Iran is one of the 3 members of the UNFCCC that had not ratified[188].

The long term goal of the Paris Agreement's is to keep the rise in mean global temperature to well below 2 °C (3.6 °F) above pre-industrial levels, but preferably limit the increase to 1.5 °C (2.7 °F), so as to substantially reduce the effects of climate change. To keep the temperature, rise below 1.5 °C of global warming, a reduction in emissions by about 50% by 2030 [3, 188]

Under the Paris agreement, each country must determine, plan, and regularly report on its emissions contributions. Countries are not forced to set specific emissions targets, but each target should be an improvement on previous targets. Unlike the 1997 Kyoto Protocol, the distinction between developing and developed countries is not clear so even developing countries should submit emissions reduction plans.

World leaders lauded the Paris agreement, but it was criticized as insufficiently binding by some analysts and conservationists. The pledges made so far under the Paris Agreement are insufficient to achieve the set temperature goals, but we have a mechanism of increased ambition. The Paris Agreement can be applied in climate litigation and force countries and energy products dealers to strengthen climate action[188]

2.9 Sustainable Development and Sustainability

There is some interrelationship among the five dimensions of energy sustainability in which the environmental state is affected by driving forces coming from the economic and social dimensions. The social state is turn, influenced some driving forces originating from the economic dimension of the energy system while the institutional dimension of energy can affect all other dimensions of energy by means of corrective policies which influence sustainability of the entire energy system.

Sustainability is a major concern today as a direct result of the serious concerns over the climate change, of which electricity generation is an important contributor[127]. Electricity is a critical product needed to support life, welfare and global sustainable development[128]. Currently, humanity is faced with a significant challenge to realize new sustainable development Goals (SDGs) by the year 2030 [101, 128]. Sustainable development and its correlation with energy became a significant global concern and issue in the 2002

Johannesburg world summit on sustainable development[129]. Determination of the most appropriate energy systems in an electricity mix is considered as a strategic approach in realization of sustainable development[131, 132]. Electricity generation systems can be assessed by a five-dimensional approach consisting of environmental, economic, social, technical and institutional sustainability as a strong measure of energy sustainability[131]. Therefore, sustainability in energy development seeks to achieve technical sustainability, political or institutional sustainability, social sustainability, environmental sustainability, and economic sustainability which is greatly realized by the development and use of renewable energy resources[3, 133].

Sustainable development requires policies that lead to reduced energy usage, and energy options with less greenhouse gas emissions, competitively priced, renewable, socially acceptable and with a reliable supply. Several measures can be adopted by governments to ensure sustainability of energy resource to power economic growth[12, 21, 189]. These measures include development of efficient energy technology options, promote the development of renewable energy sources, develop energy efficient and emissions reducing industry systems, enhance liberal trade regime for renewable and low carbon energy technology transfer from developed countries; and facilitate urbanization that uses low-carbon urban infrastructure and transport systems to achieve sustainable growth [3, 190].

About one billion people globally have no access to electricity globally while hundreds of millions more face expensive or unreliable electricity supply. This poses a significant challenge to socio-economic development particularly for developing countries. It is necessary to realize universal access by use of both grid and off grid electricity options which is goal number 7 of the sustainable development goals [191]. The main challenges facing grid electricity are insufficient generation capacity, obsolete and poor electricity transmission and distribution infrastructure, high cost of supply for remote and rural areas and high cost of power compared to locally available alternatives sources of energy[192]. Access through off grid approaches is hampered by inadequate policy and regulatory framework, lack of finance and poverty which makes electricity unaffordable for the rural poor, as millions more also content with unreliable or expensive electricity supply. These challenges further limit electrification and economic progress of the un-electrified regions to varying degrees which need further investigation [191].

A sustainable economy should have higher levels of competitive energy and resource use efficiency as well as policies which encourage these desirable conditions. The overall objective is to direct benefits of improved efficiency to deliver low carbon energy supply and improved quality of life rather than additional growth and increased energy consumption. Measures needed include development of a green fiscal reforms[193], application of progressive efficiency standards[194], setting of caps on both emissions and use of energy resource, and adoption of clean and low carbon energy conversion technologies, application of measures to that promote flexible working arrangements and limiting of working hours, income redistribution among other measures. However, these measures will only succeed if there are structural factors that continued economic growth, for example fractional reserve banking systems should be consistent with sustainability goals[189].

Energy business has significant impact on the balance of payment positions for importing and exporting countries for example the US spent approximately \$190 billion in 2014 on petroleum imports. Oil importing countries must content with energy insecurity and fluctuating price and supply of petroleum[167]. Electricity can also be imported and exported between countries leading to sharing of resources with resource rich countries especially with desirable renewable and low carbon sources like hydro and nuclear. Reducing dependence on energy imports reduces the impact of supply disruptions while promoting local investment in sustainable energy options [167].

Sustainable development and sustainability are related concepts and ideas that were introduced by philosophers, economists and scientists in the 18th, 19th and early 20th centuries[195]. Sustainable development is defined as sustained growth, sustained change or just simply development that is successful [196]. There is ever growing demand for energy to meet the ever-growing energy needs by mankind globally for the economic, social requirements, health needs, and comfort and welfare applications. Sustainability is necessary in energy and other resources exploitation so as not to compromise the ability of future generations to meet their own energy and environmental needs [197]. There is therefore need to strike a balance between global economic growth and the social wellbeing of the society to realize sustainability, and this is both a political and managerial challenge[198]. Sustainable development can also be defined as social economic change that delivers the traditional developmental expectations and targets of the people in society but under positive ecological

considerations and with due regard to the ability of future generations to meet their own needs. The concept of sustainable development has the objective of achieving economic advancement and progress while at the same time conserving the value and integrity of the environment. This calls for a tradeoff between environmental sustainability goals and economic development objectives and targets[199].

The concern for proper use of natural resources historically emerged many years ago, with publication of Carson's book called "Silent Spring" (Carson, 1962) being used as the starting point. Ten years later in 1972, there emerged the so called the 'Club of Rome' which styled itself as an independent think tank that later published a book entitled "The Limits to Growth" [200-202]. The authors of this book concluded that if the world's population and economy is to continue growing at the then rates, then the planet earth's natural resources would approach depletion. The publication of this book fueled a public debate that led to the formation of the UN 'World Commission on Development and Environment', called the Brundtland Commission, named after its chair who was Gro Harlem Brundtland, a former Norwegian Prime Minister [195, 203]. After four years of work, the "Brundtland Commission" released its final report that was entitled, "Our Common Future". It defined sustainable development as positive change that meets the needs of the present generation without compromising the ability of future generations to meet their own needs in future [203, 204]. The concept of sustainable development raises concern about what is acceptable in today and if it is acceptable or not acceptable to the next generation [139]. Today, the strategies for sustainable development aim at promoting harmony and wellbeing among human beings and between humanity and Mother Nature. Obviously, energy, especially in the form of electricity, has a central role in any effort to achieve sustainable development.

It is necessary to integrate economic, social, and environmental considerations for maximum positive outcome [205]. The 2030 Agenda for sustainable development and its framework of 17 sustainable development goals (SDGs) was adopted by the United Nations General Assembly in September 2015. Sustainable development recognizes the need to eliminate poverty and ensure equity and integrity of the global community. The 2030 agenda expects member states and countries to protect the earth from degradation by taking sustainability measures like sustainable resource production, sustainable resource consumption, and

sustainable management as well as conservation of natural resources and prevention of climate change [167, 206].

Quite often policies that protect the environment also promote innovation and profitability by organizations while organizations that are not sustainable in their operations and culture may not take sustainability measures seriously. Promotion of innovation and strict environmental regulations can enhance competitiveness and hence economic performance and progress. The link between environmental integrity and development provides a strong rationale for environmental protection. The inherent interdependence between the stability of the environment and the economy lays the foundation for sustainable development [199]. For sustainable development to be realized, public policy should promote investments in economic activities with due regard of the impact on natural environment, human and social capital, and prevention of adverse effects like pollution, social clashes, resource waste and greenhouse gas emissions [167].

Sustainable development recognizes the significance of intergenerational equity and hence no generation or group should have more rights of access to nature than others. This leads to the polluter pay principle which requires authorities to impose penalties upon those who pollute the environment and hence make them bear the cost of their impact instead of leaving it with the environment or others. Practically, sustainable development requires integration of economic, environmental, and social objects across sectors, territories, and generations. This implies that for sustainable development elimination of fragmentation of economic, environmental, and social concerns in decision making process should be done [199]. Sustainable development is a continuous process just like a journey and should never be a mere destination or event[205].

2.10 Energy and Economic Growth

Growth theories show that sustainable economic growth depends on the effective use of the factors of production of which energy is one of the factors. Energy and growth in the gross national product are interrelated. Whereas, energy is an important factor of production, economic growth leads to higher living standards which then leads to higher energy consumption[12, 207, 208]. Because of this a relationship between energy consumption and

economic growth is a crucial subject of debate in the literature for the last four decades pioneered by Kraft and Kraft[208, 209].

Energy is an important input for economic and social development, making its demand increase day by day after the Industrial revolution. Other factors contributing to continuous growth in energy demand are population increase, technological developments, and industrialization[210]. As the main input for manufacturing, we need energy to increase the welfare of all societies. However, the main challenge the world is that most of the energy is met by polluting and depleting fossil fuel sources mainly in form of coal, oil, and natural gas[211-213]. Although energy is a very important factor of production for all countries, traditional economic growth theories have not adequately covered the impact of energy consumption on economic growth to establish their exact relationship[12, 211, 214]. All operations and activities that influence economic growth and development of countries are highly dependent on energy consumption and its availability, cost, and other [211, 215]. Energy in form of electricity plays a vital role in promoting economic activities and hence growth especially for the industrial sector while at the same time providing vital input for other socioeconomic activities in all sectors of the economy [216]. Therefore, access to energy in all forms is of great concern to the international community and is therefore listed as an important agenda in the millennium development goals. It is therefore very important to understand the role and relationship played by energy services in promoting or limitation of human socioeconomic development with economic literature indicating that a country's economic growth is often proportional to the of energy by all sectors of the economy[216, 217]. There is however a conflict in pursuit for sustainable development since more energy consumption leads to more greenhouse gas emissions which cause global warming[78, 109]. Therefore according to [218], it is necessary for a country to establish the relationship between the energy consumption and economic growth before they develop any energy conservation policies. The conservation policy must be applied if studies support either conservation hypothesis or the neutrality hypothesis.

Energy consumption is an important basic indicator of both economic development and growth[219], since we generally have a strong interdependence and causality between energy consumption and economic growth. However, the direction of causality between economic growth and energy consumption is not definite or clear and thus will tend to vary from one

jurisdiction to another and one scenario to another[220]. The various relationships between energy consumption and economic growth can be grouped into four hypotheses namely growth hypothesis, conservation hypothesis, feedback hypothesis and neutrality hypothesis[221]. In the growth hypothesis, a unidirectional causality linkage from energy use to economic development is assumed, implying that energy is very important for economic growth or economic activities. In this case scenario, any reduction in energy directly and indirectly leads to economic decline. The conservation hypothesis posits a one-way causal linkage from economic growth to energy use implying that a reduction in energy consumption affects the growth in the economy or economic performance. In the feedback hypothesis, there is a two-way causal linkage between economic growth and energy consumption implying that a change in consumption in energy affects the economy, while at the same time, any change in the economy has an impact on energy consumption. There exists no causal relationship between energy consumption and economic growth for the case of neutrality hypothesis which implies that any changes in energy and economy does not affect each another[221, 222].

The various relationships existing between energy consumption and economic growth are categorized into four hypotheses. These growth hypotheses are conservation, growth hypothesis, feedback and neutrality hypothesis[218]

- i.) Growth hypothesis: in this category of relationship, consumption causes of energy causes economic growth and therefore applying the conservation policy will have a negative impact on the economic growth agenda.
- ii.) Conservation hypothesis: The assumption in the case of a conservation hypothesis is that unlike the growth hypothesis, economic growth leads to an increase in energy consumption. In this scenario, application of energy conservation policy like tariffs worth have a negative impact on the country's economic growth.
- iii.) Feedback hypothesis: The feedback hypothesis a bidirectional e relationship between energy consumption and economic growth which implies that economic growth leads to growth while energy consumption leads to economic growth.
- iv.) Neutrality hypothesis: In this hypothesis, it is assumed that there is no causal relationship existing between consumption of energy and economic growth.

It is advisable that policy makers apply the four hypotheses in developing the most appropriate energy policies for sustainable development. Since economic growth objective is in conflict

with emission control objectives which seek to minimize emissions through energy efficiency and avoidance in some cases, implementation of conservation hypothesis or the neutrality hypothesis will have a negative impact on the economic growth[218]

2.11 Sustainable Development Goals and Role of Energy

Climate action is prominent among the 17 United Nations sustainability development goals (SDG's). It is driven by the voluntary commitments the 185 Energy Compact Commitment proponents aimed at riving progress in achieving SDG-7: which targets "access to affordable, reliable, sustainable and modern energy access for all. However, d investment in renewable energy options improvements in actual SDG-7 have not kept pace with those needed to meet the the global target temperature of below a 1.5°C rise above pre-industrial levels. The gap reports indicate that the world, is already at an average 1.1°C above pre-industrial levels, will probably exceed 1.5°C for at least one year between 2023 and 2027, which will almost certainly be the warmest five-year period ever recorded. The world needs practical, affordable, and reliable sustainable energy alternatives to replace fossil-based resources. The Climate Action, one of the UN's 17 Strategic Development Goals⁷, focused on reduction of climate change and its effects on the ecosystems, along with Green Chemistry has, for over 30 years, helped scientists improve improve sustainability and reduce dependence on fossil fuels by substituting fossil fuels with renewable sources leading to shift in attention of technical resources towards more sustainable alternatives. However, high cost, competition over land use, and limited production are some of the barriers to the development of practical options for non-fossil-based resources. Besides fossil fuel use reduction other measures that can cut down emissions are carbon capture and sequestration and energy efficiency measures.

There are almost 770 million people globally with no access to electricity, most of whom are in Asia and Africa. Covid-19 crisis ended many years of continued progress and worsened the already low energy purchasing power of many households particularly in developing countries. Available data suggests that the number of people with no access to electricity slightly changed between 2019 and 2021, by declining an average of 9% a year between 2015 and 2019. For Sub-Saharan Africa, the number of people with no access to electricity increased in 2020 for the first time since the year 2013, with Sub-Saharan Africa's accounting

for 77% of the global population having no access to electricity which is a rise from 74% before the pandemic[223].

For the world to attain full electricity access by 2030, about 100 million should be connected to the grid annually. Unfortunately, the world is not on track to achieve this target with a conservative benchmark examining existing and planned policies and strategies showing that about 672 million people will remain with no access to electricity by the year 2030 of which 85% will be in Africa. On the positive note, many developing countries in Asia are on track to attain the universal access by 2030. Over USD 35 billion or just 2% of current global investment in energy to realise full access by 2030. Other than financial barriers, attaining universal access can be deterred by low power demand in some remote areas, which calls for innovative solutions like decentralised generation and other off grid measures[223].

It projected that beyond the year 2030, most global populations will have access to the grid with some initially getting access through off-grid power solutions. This shows the importance of grid-compatibility by the off-grid systems used today [223].

Electrical generation for residential use is an important goal of SDGs (17 UN goal) and UN-Habitat III (14 goals) which can be realised by use of renewable energy resources. Adequate investment in energy and electricity generation from renewable sources is necessary to achieve development in energy sustainability [224].

2.12 Energy and Sustainable Development

Energy plays a very important role in socioeconomic development by virtue of its role in domestic, commercial, and industrial heat and electricity applications making it an engine of a country's socio-economic progress. The pursuit for economic development, which is a primary objective of all countries, leads to high consumption of energy, most of which is derived from nonrenewable sources. There are four hypotheses that explain the relationship between economic growth and energy consumption. The growth hypotheses are the conservation hypothesis, growth hypothesis, feedback, and neutrality hypothesis. For most scenarios, energy consumption and economic output are positively correlated. On the other hand, energy intensity has been declining over time and is lower for developed countries compared to the less developed economies. Energy scarcity in an economy is undesirable

because it suppresses economic growth, while an increase in availability and access to modern energy tends to reduce the significance of energy as a driver of economic growth and development over time. This study showed that there is generally a causal relationship between economic growth and growth in electricity consumption. However, energy consumption alone does not lead to economic growth, instead it requires a combination of factors like a favorable overall energy mix, capital formation in the economy, energy efficiency or intensity, energy price, technological sophistication, while the proportion of low and high energy goods and service should be applied in a way that energy consumption is positively applied to foster sustainable development. The relationship between energy consumption and economic development may vary from time to time and from country to country, hence the need to develop energy policies on basis of research for a given country to ensure that energy policies foster economic growth in a specific country[12].

Energy is an important input for economic and social development, making its demand increase day by day after the Industrial revolution. Other factors contributing to continuous growth in energy demand are population increase, technological developments, and industrialization[210]. As the main input for manufacturing, we need energy to increase the welfare of all societies. However, the main challenge the world is that most of the energy is met by polluting and depleting fossil fuel sources mainly in form of coal, oil, and natural gas[211-213]. Although energy is a very important factor of production for all countries, traditional economic growth theories have not adequately covered the impact of energy consumption on economic growth to establish their exact relationship[12, 211, 214]. All operations and activities that influence economic growth and development of countries are highly dependent on energy consumption and its availability, cost, and other [211, 215]. Energy in form of electricity plays a vital role in promoting economic activities and hence growth especially for the industrial sector while at the same time providing vital input for other socioeconomic activities in all sectors of the economy [216, 225]. Therefore, access to energy in all forms is of great concern to the international community and is therefore listed as an important agenda in the millennium development goals. It is therefore very important to understand the role and relationship played by energy services in promoting or limitation of human socioeconomic development with economic literature indicating that a country's economic growth is often proportional to the use of energy by all sectors of the economy[216,

217]. There is however a conflict in pursuit for sustainable development since more energy consumption leads to more greenhouse gas emissions which cause global warming[109, 226]. Therefore according to [218], it is necessary for a country to establish the relationship between the energy consumption and economic growth before they develop any energy conservation policies. The conservation policy must be applied if studies support either conservation hypothesis or the neutrality hypothesis.

The use of energy derived from non-depleting sources is an essential component of sustainable development which demands economic growth in a clean and healthy environment for both current and future generations. The concept's impact on the design of policies has grown dramatically both at national and international level making it a crucial component of policy considerations by governments, businesses, and international organizations [227].

Sustainable development of countries needs a stable supply of energy that is long-term, affordable accessible, and capable of universal application without detrimental influence on society. Not all renewable green energies are entirely clean, but with many available options, shifting to green renewables within the context of long-term sustainability will lead to a cleaner system[29],[2]. From different studies, the main objective for the evolution of energy systems is to realize sustainable development. There are four main themes which are essentially sub-goals of developing sustainable energy are:

- i.) social and economic development.
- ii.) energy access.
- iii.) energy security; and
- iv.) combating climate change[227].

The energy sector is an essential component of social and economic development because of the link between economic activity at levels of energy consumption. On a global scale, we have a positive correlation between per capita income and per capita energy use. The use of renewable green energy provides an attractive alternative for socio-economic development, job creation, reduced emissions, and realization of the sustainable development goals (SDGs). Communities that that can produce, share, sale, and store renewable and sustainable energy green energy have a leading role in the development of a decentralized, digitalized, and decarbonized power system. However, to realize this needs significant collaboration between

various stake holders and enabling technologies like smart grids, microgrids, decentralization of generation, and demand side energy management infrastructure [227].

Energy access regardless of the source has a strong correlation with growth measures, particularly for the developing countries. The seventh Sustainable Development Goal (SDG7) focuses on the need for affordable energy to guarantee socioeconomic equality and justice for all. Access to energy is a fundamental necessity that should be available to all people, making energy affordability a key factor in sustainable development. As a result of this commitment, the percentage of persons who cannot afford to keep their homes warm winter declined by 6.9% between 2012 and 2019 in Europe, although the percentage was rose again to about 8.2% in 2020[61, 227]. Therefore, cost and energy access are critical to achieve sustainable development goal number 7.

The original idea of energy security was limited to guaranteeing an adequate supply of oil and mitigating the macroeconomic consequences of oil supply disruptions. The renewable energy sources are more uniformly dispersed globally and are generally less traded in the market which leads to a reduction in the energy imports, diversification of power sources, reduced sensitivity to energy price, changes which significantly enhances energy security compared to fossil fuels. There adoption of renewable and green energies contributes to improved sustainability of energy products and services[12, 227].

The use of renewable and green energy sources for power generation reduces emissions to which slows down the progression of the climate change and reduces the environmental and health risks sources of energy associated with power generation. The electricity sector continuously benefits from rapid advancements with the share of renewable sources rising from 19.7% in 2010 to 26.2% in 2019, a momentum that should be maintained and enhanced [227].

Many growth theories indicate that sustainable economic growth relies on the effective use of the factors of production of which energy is one of them. Whereas, energy is an important factor of production, economic growth leads to higher living standards which then leads to higher energy consumption[12, 207, 208]. Because of this a relationship between energy consumption and economic growth is critical and should be well defined and understood and has been an interesting subject for the last four decades pioneered by Kraft and Kraft[208,

209]. There is overwhelming evidence from many studies that energy consumption is closely linked to economic growth and development. These studies have yielded different results because of differences existing between countries investigated in the studies. In the pioneer work by, Kraft and Kraft (1978), a unidirectional causality was established running from economic growth to energy consumption for the United States of America between 1947–1974 [12, 214].

2.12.1 Energy in Sustainable Development

It is essential to use energy derived from non-depleting sources for sustainable development which demands economic growth in a clean and healthy environment to meet the needs of current and future generations. The impact of this concept has grown dramatically on policy design both at national and international level thus making it an important component of policy considerations by governments, businesses and international organizations keen in sustainability [227].

Sustainable development of countries needs a stable supply of energy that is long-term, affordable accessible, and capable of universal application without detrimental influence on society. Not all renewable and green energies are entirely clean, but with many available options, shifting to green renewables within the context of long-term sustainability will lead to a cleaner energy systems[29],[2] .

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- vii.) Energy security; and
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Communities that can produce, share, sale, and store renewable and sustainable energy green energy have a leading role to play in the development of a decentralized, digitalized, and decarbonized power system. However, to realize this needs significant collaboration between various stake holders and enabling technologies like smart grids, microgrids, decentralization of generation, and demand side energy management infrastructure [29, 227].

Energy access regardless of the source has a strong correlation with growth measures, particularly for the developing countries. The seventh Sustainable Development Goal (SDG7) focuses on the need for affordable energy to guarantee socioeconomic equality and justice for all. Access to energy is a fundamental necessity that should be available to all people, making energy affordability a key factor in sustainable development. As a result of this commitment, the percentage of persons who cannot warm their homes in winter declined by 6.9% between 2012 and 2019 in Europe, and then 8.2% between 2019 and 2020[61, 227]. Therefore, cost and energy access are critical to achieve sustainable development goal number 7.

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2.12.2 Sustainable Energy

Sustainable energy refers to energy sources that cannot be depleted and can forever remain viable. Sustainable energy does not have to be renewed or replenished; but should meet the needs of humanity without running out or deteriorating. Furthermore, sustainable energy

should not harm our environment or should have minimal risk, sustainable energy should not cause or accelerate climate change and should be affordable. There is always a cost that is incurred when creating and building technologies and systems to capture sustainable energy, but the energy sources themselves are typically accessed freely. The sustainable energy sources include wind, hydro, /water, solar and geothermal and are generally considered inexhaustible and are widely available to almost everyone[2, 228].

The energy crisis of 1973 created significant public interest in energy sustainability especially the global climate change mitigation targets which demand changes in the economic sectors. There is a global consensus that the climate targets need rapid electrification of the economy and decarbonization of the power sector[229]. Energy models are used to identify development pathways for the energy sector to achieve environmental goals[229, 230]. The main challenge with energy models is that most of them oversimplify interrelations with other sectors or parts of the system since most of them focus on certain parts of the energy system like electricity and heat supply thus they yield significantly different results from those of multi-sectoral approach[229]. Modern energy requirements require energy system models which incorporate technical, societal, environmental and institutional aspects of energy systems which constitute the main dimension of sustainable development [231]. Today, one of the greatest challenges facing humanity is the fear for the looming climate change occasioned by ever increasing greenhouse gas emissions, most of which are derived from energy consumption[232]. It is because of the urgent call to reduce greenhouse gas emissions and its consequences that many countries globally are now than ever, committed to reduce their greenhouse gas emissions by the order of 60-80% which calls for use of effective and reliable energy and electricity modelling tools even as they seek to rapid economic development [232]. It is therefore important to understand the prevailing relationship between energy consumption and sustainable development so that the right or appropriate policies are put in place.

2.12.3 Sustainable Versus Renewable Energy

The terms “sustainable” and “renewable” are often used interchangeably, but the difference between the two is the possibility of being replenished. Sustainable energy is theoretically inexhaustible, and so cannot be depleted because sustainable energy sources don’t need to be replenished e.g., the sun or wind and water do not need to be created or replaced. On the

other hand, renewable energy is theoretically exhaustible and uses resources from the earth are replenished naturally e.g. crops and biomatter. Renewable energy sources which include straw, manure, ethanol, from sugarcane and corn can be obtained from sources that can be planted and farmed to generate renewable energy. [228].

Sustainable energy or electricity refers to the generation and supply of electricity in a way that does not compromise the ability of future generations to meet their own energy or electricity needs[233]. It can also be defined as energy sources that do not get depleted in a time frame that is relevant to humanity and hence contribute to the sustainability of all species[234]. Sustainable Energy, just like sustainable development requires significant changes in the way things are done and the exact things that we do with effects on the industrial, production, social infrastructure, and value systems[215, 235]. Whereas energy is an indispensable part of economic development, it is a leading source of greenhouse gas emissions, associated with global climate change that is currently threatening the very existence of man[3, 21, 235]. The global sustainability challenge today is realization of energy sustainability, mitigation of the climate change and economic growth simultaneously[3, 21, 215]. To balance economic growth and sustainable energy targets, it is necessary to decouple growth in energy consumption economic growth and development[211]. The development of clean energy would unlock many challenges to sustainable development[21, 58, 110].

Energy sustainability refers to the provision of energy services and products for all people at present and in the future, in a manner that sufficient to provide necessities, not overly detrimental to the environment, at affordable cost and price, and acceptable to people and their community. The broad and growing nature of energy makes sustainability important. This is further compounded by high environmental impacts associated energy exploitation and importance of energy to the living standards and economic development of all countries [29, 61]. A shift to sustainable energy requires several measures like employing advantageous energy carriers, use of efficiency energy systems, mitigating lifecycle environmental impacts, and no technical and social measures like living standards and peoples lifestyles and choices, affordability, economics, and societal perception and acceptability and social equity[2, 236].

Energy Sustainability (ES) in electricity generation has become a priority issue because of its fast growth in demand, high emissions and close relationship with climate change and hence global commitment to combat global warming and related consequences. Strategies that can be applied to reduce greenhouse gas emissions in power generation include high operational efficiency of power system and a shift to sustainable energy sources [3, 237]

2.12.4 Dimensions of Sustainable Energy and Electricity

The transition into sustainable energy requires the determination of the most appropriate energy sources in the power industry as a strategic factor. Five comprehensive aspects used in energy sustainability assessment are the environmental, social, economic, technical, and institutional[37]. Energy investment decision making processes should be guided by a careful evaluation of the sustainability of generation and alternative choices[238]. Multicriteria analysis is important in planning energy systems and projects which are complex in nature. Figure 2-5 shows the 5 dimensions of energy sustainability assessment.



Figure 2-5: The five dimensions of energy sustainability[3]

From Figure 2-5, the five dimensions of energy sustainability are economic, environmental, social, technical, and institutional.

Energy system planning is a complex undertaking and projects represent the importance and necessity of multi-criteria evaluation. Sustainability assessment refers to a tool used by decision-makers and policymakers to understand the do's and don'ts to achieve a sustainable society and shows relationship between different projects aimed at realising sustainable development[37, 39]. The introduction of the concept of sustainable development, made sustainability indicators important in the evaluation of alternatives for achieving sustainable development. It is important for decision-makers, policymakers, and members of the society to understand that current decisions affect the future environment, welfare, and socio-economic development. Sustainability assessment tool is applied by decision-makers and policymakers the impact of the decisions they make [37]

2.12.4.1 Environmental Dimension

The environmental dimension evaluates the environmental impacts of energy using criteria like the amount of their pollution and environmental effects. Since the energy sector is a leading source, knowledge of the greenhouse gas emissions from different energy sources and power plant technologies helps in effective reduction of greenhouse gas emissions, and other environmental impacts. Other environmental pollutants can be divided into three parts,

- i. Quantity or level of pollutants released like audio, soil, water, air, etc.,
- ii. Quantity of non-recyclable waste, and
- iii. The amount of greenhouse gas emissions.

An important criterion considered in the environmental dimension number of natural resources needed like of land use, water, fossil fuels, etc. to exploit energy resource. Emphasis in the environmental dimension, is the environmental impact that the use of each energy resource and power plant has on land and other natural resource [37].

The environment should never be allowed to absorb more than it can contain, naturally or artificially[15]. Environmental sustainability is concerned with the integrity of natural environment and its ability to remain resilient and productive in support of humanity[126]. Environmental sustainability is further concerned with the integrity and carrying capacity of the natural environment to sustain humanity as a waste sink and source of raw materials[137]. The main environmental costs of energy include the cost greenhouse gas mitigation investment, direct and indirect economic impact of emissions, environmental external costs,

radionuclides external costs, cost of energy related accidents and penalties from pollution. Therefore, an environmentally sustainable energy systems should maintain a stable resource base, avoiding energy resource over-exploitation, and avoid depleting non-renewable resources through development of adequate substitutes[132].

The main environmental dimension indicators for energy technology assessment include, the GHG emissions, environmental external costs, radionuclides external costs, severe accidents perceived in future and fatal accidents from experience. Additional environmental indicators are land use and solid waste. Life cycle emissions of GHG emissions in kg (CO₂-eq.)/kWh are selected to assess electricity generation technologies in line with policies like the EU environmental policy on climate change mitigation[239]. GHG emissions in kg CO₂eq./kWh were selected instead of external costs of GHG emissions because of the large uncertainties related to evaluation of external costs of GHG emissions. Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is an issue for the environment as well as human society because of the rising global temperatures which have serious consequences on the economy and social life [239].

2.12.4.2 The Social Dimension of Energy

The social dimension of sustainability is often neglected despite its important role in sustainability assessment leading to irreparable outcome in the implementation of sustainability of energy projects[2, 240]. Social sustainability is concerned with the rights of the community as measured by the level of social acceptance and access to the energy resource and systems by the people [15]. Social sustainability is the ability to preserve desirable social values, institutions, traditions, and social characteristics of the society before and after a project or an intervention. It is also concerned with social justice and therefore addresses aspects like labor practices, variance in production standards, and promotion of equity among all people[140-142]. Social sustainability can be achieved by the selection and development of technology and power plants that provide adequate power and employment to local communities and that don't interrupt or interfere with their established way of living and value system [126, 133, 143]. The social dimension measures the social acceptance and society access to energy resources and the dimension refers to two major issues i.e., energy distribution or the energy spread and affordability or the financial effect. Additionally

development of energy resources and power plants has a positive effect on employment as a social effect[37]. Therefore, social sustainability implies that people are important because development is basically about the people themselves. Principles that should be applied in energy development to realize social sustainability include accountability, empowerment, participation, cultural identity, and institutional stability[137].

Social sustainability assumes two types of sustainability i.e., social capital and human capital. Social capital is concerned with quality of public services like good education, water, infrastructure or a supporting culture and value system. Human capital is primarily concerned human skills, level of motivation and loyalty of employees and business partners in their own capacity [198]. Therefore, human capital is an intrinsic phenomenon of an individual or individuals while social capital is concerned with communal or common physical projects, infrastructure or facilities meant to improve the quality of human beings in each social system. This implies that sustainable energy systems should have a positive impact on both the human and social capital of society.

For energy resources and electricity systems to be socially sustainable, they should be characterized by equity, reliable supply of social services, address gender equity, facilitate political stability, address accountability issues, and nature participation in their governance systems [139]. Social sustainability requirements call for energy practitioners, organizations, and countries, local and international organizations to go beyond just energy solutions and ensure holistic approach in as far as energy transition is concerned. Energy transition should address human physical and health, system and human safety, human rights, and dignity for sustainable energy development to be achieved.

Energy policies necessary to realize sustainability should be guided by a mixture of robust, objective, empirical and theoretical principles that consider the impact not just to the current generation, but equally on future generations. Energy resources and electricity systems should consider socio-technical impacts on man and machines for them to be socially acceptable. Adoption of new electricity or energy technologies should bear in mind that systems are operated by man and should therefore be acceptable and comfortable by design and adequate capacity building should be done for man to be comfortable and therefore embrace new ways and systems[2, 3]. The impact of the technology change or acquisition on current and future

financial systems, school system, labor market composition, organizational culture and political aspirations of the people should be considered in the energy transition if it has to be sustainable and avoid failure or negative perception by the people[241]. This implies that man is a very important aspect of the energy transition and should be at the center of the transition and be involved using various participatory methodologies, otherwise the transition may never succeed.

Any social evaluation of energy systems should consider social acceptability, expected job creation, and other social benefits of the energy systems[135]. Significant social indicators for energy and electricity technologies are related job opportunities, health effects, food safety and security risk and work-related accidents and fatalities. Technology specific job opportunities in person-year/kWh indicator are based on the average amount of labor used to produce a unit of electricity[128, 242]. The quality of electricity or energy related work is addressed by Work Quality indicator is based on knowledge and training of average worker in each technology chain, using an ordinal scale indicator [239]. A system is said to be socially sustainable if it guarantees distributional equity, provides social services like education, health, guarantees gender equity as well as political accountability and adequate public participation of stakeholders[139].

2.12.4.3 Economic Dimension

The economic dimension of energy sustainability is concerned with economic viability of energy investments and is used to evaluate whether energy is affordable for consumption by the society or not. The society cannot afford costly energy supply and hence would not consume it, making the return on Investment (ROI) for investors low and unattractive investment[12, 186]. The criteria in the economic dimension includes initial investment, the cost of construction for power plants, cost of operation and maintenance, cost of transportation, fuel costs, and cost of external effects that are all taken into account in calculating the cost of electricity production[37, 39]

Electricity generation and distribution is a big business in all countries while production and export of energy resources like fossil fuel sustains many countries' economies with some almost entirely dependent on oil and gas exports. Export of energy production equipment like generators, turbines, boilers, and other plant equipment represents a substantial market

opportunity for many countries like the United States and often generate high-value jobs[141, 168].

Economic sustainability seeks to maintain the operational stability in terms of liquidity and cash flow and ensure fair or reasonable income and benefits to investors and other stakeholders in energy systems[198]. Electricity is the most multipurpose energy carrier globally, and therefore it is highly linked to human and economic development [243]. For economic sustainability to thrive, organizational policies and operations should not retard economic progress, development, or affluence of society[244]. Through economic sustainability, humanity can maintain independence and have unlimited access to the required energy resources. Economic sustainability is achieved from energy systems if they remain intact while activities and processes are equitably accessible to for use [203]. Therefore, economically sustainable energy or electricity system must continuously produce goods and services to manage debts, pay bills, pay employees and ensure sectorial [167]. Energy systems and organizations should remain profitable and useful from one generation to another generation[245]. Therefore, this implies that energy systems are economically sustainable if they are operated profitably by investors or organizations. The various elements of economic dimension of energy sustainability include corporate sustainability, energy costs, supply disruption losses, energy import bills, energy technology and service market.

In economic evaluation of energy systems, the criteria for evaluation include total cost of investment, operation and maintenance cost, fuel cost of generation, electricity cost, net present value (NPV), service value and equivalent cost of the energy system[135]. The Economic dimension in sustainability assessment of energy technologies and projects is significant since energy or electricity supply cost influences technology adoption and penetration. Indicators that address economic dimension of energy sustainability assessment in electricity and heat generation and supply include the private or investors costs involved, the fuel price increase sensitivity, energy or plant average availability factor, costs involved in grid connection, energy or plant peak load response, and energy security of supply. Very important economic investment indicators are private costs, availability factor and costs of electricity grid connection[239]. Goods and services should be produced in a continuous manner in an economically sustainable system to be realized. should produce goods and services continuously, to maintain sustainable levels of debt, and [139].

2.12.4.4 Institutional Dimension of Energy Sustainability and Development

The institutional or political dimension of energy sustainability is concerned with the governance of the energy sector which is achieved by setting and implementing policies and regulations which enable different political institutions to influence the governance choices in the energy sector[3, 144]. The institutional dimension of energy sustainability is used to determine the degree of local participation in the management and control of energy systems. It portrays local skills, national development plans, local regulations and the degree of protection consumer and investor protection. It is used to evaluate the political decisions made about the future structure of the energy sector and refers to entities that define the structure of the industry due to the external world. Hence, the institutional dimension represents issues related to political stability and foreign policy of the energy system[3, 37].

This political dimension of energy sustainability deals with the strategic planning and definition of the energy, related systems, and processes. The institutional dimension of sustainability defines the role of local participation in the control and management of energy resources and energy systems[141, 142]. The institutional dimension embodies elements like local ownership, participation, local contributions, local skill base, local policy and regulation, protection of investors and consumers and sharing of resources and benefits accruing. This dimension is the one that defines the system structure and framework of processes, systems and policy decisions which affect the project or investment[15, 126]. There is evidence that highly or adequately institutionalized countries with efficient and effective energy related institutions are more successful in managing the energy transition. This is because the institutions encourage innovation, efficient resource allocation and set desirable policy, legal and financial measures and instruments which are enablers of sustainable energy transition [146].

Sustainable development requires organizations and nations to develop new energy technologies, new policy directions and new business models which require control models, rules and regulations to support the energy transition[246, 247]. Governance of energy sectors must be streamlined to build the legal and institutional framework that will guarantee supply of energy in a sustainable manner to support sustainable development.[133, 144]. Examples of measures needed to build the institutional capacity is the development of green fiscal

reforms for the energy sectors to ensure progressive standards of efficiency.[194], fixing of emission caps, recycling of energy resources and materials, promotion of renewable energy technologies and systems, support of flexible working, arrangement for optimum resource use and allocation, income redistribution and many other measures. However for such measures to succeed, nations and institutions should address structural factors that make economies sustain growth[189].

Transition studies show that, whereas technological innovations and market actors are the main drivers of change, extensive studies show that it is governance systems that influence the distribution of the benefits of new technologies to the society which is an important requirement of sustainability[133, 144]. The road to the global low-carbon transformation should deal with the climate crisis is within reach, but this requires political actions from world leaders. There is need for action along multiple approaches and models globally that can be scaled up and adapted to suit specific national prevailing circumstances. Cost-effective a low-carbon technology is available in many fields with several under research but the rate of adoption is still a serious concern because governments need to put in place the right policies, regulations and a facilitating legal framework for faster and successful adaption [159, 248].

2.12.4.5 Technical Dimension

Technical sustainability of energy systems refers to the ability to meet the current and future demand in a safe and efficient manner with the use of clean sources of energy and technology [133]. Unsustainable production and consumption of energy resources is the main cause of environmental damage in many organizations and countries globally[143]. To realise sustainable development calls for changes in industrial processes and systems, in terms of the type and quantity of energy and other resources for waste management, emission control as well as product and service range or type[2, 249]. Through the development and adoption of appropriate technology, humanity can make development of energy sustainable. Engineering and technology are closely linked to sustainability, but the engineering input so sustainability must be in partnership with other interests by application of constraints to the three pillars of sustainability which are social, environmental, and economic pillars. All engineering systems, products, operations, services, and infrastructure have designed and actual life after which

they should be subjected to sustainability analysis by application of three measures in order of priority. These measures are reuse, recycle and disposal [250].

The technical dimension shows the ability of the energy system to meet the present and future needs of the society by assessing the structure of the energy system, its infrastructures as well as its the inputs and outputs. Efficiency is a very important indicator of technical sustainability and can be evaluated by three criteria, i.e. energy efficiency, distribution system efficiency, and conversion system efficiency. Availability and access to technology and technical knowledge needed to exploit energy resources is very important. Ease of access to technology needed for power generation is a very important criteria for selection of electricity generation alternatives. The technical dimension is qualitative and are defined by energy and policy experts[3, 37].

2.13 Non-Renewable Sources

Nonrenewable energy resources cannot be replaced once used causing a major challenge to humanity since they supply most of our energy needs. These energy resources include coal, natural gas, oil, and nuclear energy. Non-renewable energies are derived from sources that run out or will not be replenished in our lifetimes or even in many, many lifetimes to come. With the time for fossil fuels formation being 360-300 million years ago called the Carboniferous Period. These hundreds of millions of years ago are older than the dinosaurs and the Earth had a different landscape compared to what we have today as it was covered with wide, shallow seas and swampy forests where the Plants, algae, and plankton grew in these ancient wetlands, absorbed sunlight, and created energy through photosynthesis and upon death, the organisms drifted to the bottom of the sea or lake. Over time, these dead plants were crushed under the seabed, as rocks and other sediment piled on top of them, leading to the generation of high heat and pressure underground turning them into fossil fuels i.e., coal, natural gas, and petroleum in huge underground pockets referred to as reservoirs of these non-renewable sources of energy all over the world[36, 251].

Other than fossil, biomass energy which relies on biomass feedstocks like processed plants can include crops such as corn or soy, as well as wood which should be replenished by people. If the people do not replant these biomass feedstocks as fast as they use them, biomass energy becomes a nonrenewable energy source.[251]

If nations want to implement the Paris Agreement and prevent the global temperature from increasing by more than 2°C, about 60 % of the oil still available, and 90 % of the coal, still available in mines underground should remain unused. Therefore, mankind should limit and stop using fossil fuels to save ourselves from a climate disaster[188].

2.14 Renewable Energy Sources

Renewable energy sources consist of a broad range of continuously replenishing natural energy resources and technologies. A renewable energy system is designed to convert energy in form of sunlight, wind, stored water, sea-waves, geothermal heat, or biomass to produce heat or electricity without exhausting the energy resource. [252]. The intermittent nature of sources like wind and solar causes challenges in grid integration while different power systems have different ability of grid integration based on system characteristics and resource characteristics. [252].

Renewable energies consists of those that use the virtually limitless radiation from the sun which include solar power, biomass, and hydrogen from solar water splitting, and renewables that originate from other forces of nature like hydroelectric, wind, geothermal and marine power. Some renewable energy technologies are more mature in development than others e.g. solar-based technologies, including algae oil and hydrogen from solar-driven water splitting, are less developed and their role in a 30-year decarbonization may be more difficult to assess, but have, nonetheless, been identified as potential candidates for the long-term sustainable energy plans based on their potential for cost-effective conversion of low-carbon footprint solar energy to fuel.

Renewable energy sources have been identified as the main solution for mitigation of greenhouse gas emissions, climate change, and environmental pollution[143]. Renewable energy sources (RES) can greatly contribute to economic, social, and environmental energy sustainability. Renewable energy sources improve energy access for most of the population because they are often locally available, reduce greenhouse gas emissions and may create local socioeconomic development opportunities through job creation and improved local economy. [253]. Before the industrial revolution, solar energy was the most readily available form of energy for direct solar application like drying. This changed with the industrial revolution as fossil fuels became the dominant source of energy. Fossil fuels constitute the main class of

energy sources that cause severe environmental pollution and are thus the main target of substitution with renewable and low carbon sources. The challenge of this substitution is that it may impact negatively on human development[254]. Sustainable social and economic development goals cannot be achieved without access to clean, reliable, and affordable energy resources and supplies[101, 132, 254].

As the world's population and economy keeps growing, so is the energy demand, a scenario that automatically increase the demand and consumption of conventional sources of energy, particularly fossil fuels [167, 255]. Renewable energy resources can be used as substitutes for fossil fuels. These sources are characteristically ideal to achieve sustainability in energy use as one of the basic requirements of sustainable development [256]. Therefore, replacement of fossil fuels with renewable energy sources in electricity generation is an important to reduce carbon emissions[205].

Renewable energy-based power generation reached an all-time high, exceeding 8 000 TWh in 2021, which represented an increase of 500 TWh above the remixable based generation in the year 2020, with generation from wind and solar PV increasing by 270 TWh and 170 TWh, respectively. However, the generation from hydro reduced by 15 TWh in 2021 because of effects drought, notably in the United States and Brazil. Nuclear power generation which is another low carbon source increased by 100 TWh. [161].

Renewable energy sources come from naturally occurring sources which replenish themselves through natural forces. As a source of clean energy that is inexhaustible, renewable energy sources have a significant role to play in the energy transition [257]. Although renewable in nature, their consumption should allow for natural replenishment for them to be renewable and competitive [255]. Strategies to improve access and consumption of renewable energy sources include improvement in conversion efficiency, use of energy storage technologies to deal with fluctuating nature and policies that discourage more consumption of fossil fuels [254].

There are increasing opportunities for companies to increase the use of renewable energy through development in data-driven technology which can help to better understand on real-time basis, internal energy consumption and demand, which may provide information required to control cost. Such information can assist investors in negotiating energy supply contracts that are more appropriate for their unique consumption and demand patterns[258]. Energy

planners face challenges in energy planning because of challenges like unequal distribution of natural resources, limited financial resources and other considerations. Factors considered in energy evaluation include economic, institutional, technological development, energy security, environmental protection, and prevailing state of the energy market[256]. For energy systems to be sustainable, the consumption should bear in mind the limits of resource supply and the environmental and social impact[259]. Maximum advantage should be taken of immense resource supply for renewables like geothermal, solar, hydro and wind[139].

Although renewable energy sources have significant advantages, their consumption is also associated with challenges like low conversion efficiency, unsteady supply, poor conversion efficiency, and general variability and unpredictability in supply. These weaknesses can be addressed by technological advances and application of computer hardware and software which can enhance optimization and hence create stability and reliability in renewable energy supply and use [260]. Since energy production and consumption accounts for over two thirds of the total greenhouse gas emissions and over 80% of Carbon dioxide emissions, countries that seek to meet the long-term climate objectives of the Paris Agreement must develop measures and strategies to mitigate emissions from power plants and other energy related activities. Countries should individually and collectively tackle their challenges through right and effective energy policy measures[261].

Strategies and measures that can be adopted by countries include on site power generation which involves generating power at the location where it is used like photovoltaic panels installed on buildings, farm-based biogas plants, use of geothermal heat pumps located next to the building, and combined heat and power or cogeneration as well as energy saving and efficiency measures. Another strategy to use renewable and low carbon energy is the use of interconnectors whose role is to physically link different grids or countries for more interconnection needed to ensure the countries can import electricity from low carbon producers like France mainly from nuclear and Sweden and Ethiopia with huge hydro potential as a strategy for de-carbonization of electricity [262]. The purchase of green power through Renewable Energy Certificates (RECS) also known as green tags, green energy certificates, or tradable renewable certificates is another important strategy in promoting electricity generation from renewable sources [256].

2.14.1 Benefits of Renewable and Sustainable Energy

As a result of human activity, the average global temperature has grown 1.5 degrees hotter since the industrial revolution which is much faster than any increases witnessed in the pre-industrial revolution times mainly because of burning of fossil fuels for energy leading to greenhouse effect with carbon dioxide (CO₂), being the main source[228]. The reason is that Carbon particles are trapped in the earth's atmosphere, between the ozone layer and the surface thus insulating planet earth and warming it up. This is the main cause of the catastrophic effects like melting of polar glaciers causing the rise in sea levels, extreme weather events like hurricanes, heatwaves and floods and other impacts. These cause damage to the environment and undue harm to the health of people globally. There is however some hope even though humans caused irreversible damage to the environment maintaining and mitigating repercussions for future generations by stopping or minimizing greenhouse gas emissions by transiting to sustainable and renewable energy sources[93, 160, 228].

Consumption of renewables significantly reduces total greenhouse gas emissions and consumption of renewable energy resources e.g. between 1990 and 2012, greenhouse gas emissions (GHG) in European Environmental Agency (EEA) having 33 member countries declined by 14% while GHG emissions per capita reduced by 22% over the same period [263] resulting from higher consumption of renewable energy. In the US, the same scenario was witnessed between the year 2006 and 2014 [264] which leads to environmental and socioeconomic benefits with less environmental impact from use of renewable and low carbon energy sources which also creates jobs and social capital in local communities [173].

Higher generation and uptake of renewables by utilities paves the way for a low carbon future, but the consequences their intermittency on the existing grid system should be mitigated by application of advanced technology, better planning, and increased flexibility to guarantee smooth transition to a renewables-dominated electrical grid[265].

The benefits of transitioning to sustainable energy are many and include improving health.

i. Improves Public Health

Many public health issues are related to the use fossil fuels like coal, oil and natural gas like neurological damage, heart attack, cancer, respiratory complications, and premature deaths.

This is because use of fossil fuels releases pollutants to air and water which negatively affect surrounding communities and environments. These associated health risks can be eliminated by using sustainable energy instead of fossil fuels since they typically emit no direct pollutants that can harm public health. [228].

ii. Creates Local Jobs

Sustainable energy can stimulate local community development since most facilities and sustainable energy infrastructure are installed locally or in the same region which local jobs and improve the local economy. Money that could be spent importing energy from fossil fuel companies, can be used for other development activities[228]

iii. Decreases the Carbon Footprint

The energy sector is a leading contributor to global greenhouse warming due to over reliance on fossil fuels in power generation, thus a shift to sustainable energy is a major option. Sustainable energy, creates zero carbon emissions and can offset the need for fossil fuels which emit significant quantities of greenhouse gases.[228].

iv. Long-term Cost is More Affordable

Sustainable energy resources are easily available and are affordable compared to traditional energy resources. Although access or installation cost can be high, the long-term investment pays off since they often have no fuel cost and have relatively low operation and maintenance costs [228].

v. Energy Security

Sustainable energy is a reliable form of energy as will never deplete and eliminates energy imports whose supply can face interruptions and price fluctuations. Sustainable energy additionally conserves the planet's natural resources and reduces environmental pollution[228].

2.14.2 Limitations of Renewables in Power Generation

For remote areas, the renewable energy sources and technologies are competitive energy options although they encounter barriers like limited access to capital for the for low and medium-income population. [29, 266]. Other barriers include:

Most renewables have high investment and energy costs making them less competitive as compared to conventional or nonrenewable options particularly in terms of initial cost of the project.

The renewable energy sources often require support against nonrenewable sources in forms like tax incentives, subsidies, as well as other policy and legal and financial instruments like higher feed in tariffs.

Some renewable energy sources and technologies suffer from lack of information, critical infrastructure, and capabilities to develop renewable energy projects or markets[266].

2.14.3 Renewable Electricity Generation Opportunities and Challenges

Many studies have shown a very strong correlation between energy, the environment, and sustainable development. Renewable energy sources are needed for a community to achieve sustainable development, since they have limited impact on the natural environment. [12, 37]. Electricity generation from renewable energy resources like solar, wind, geothermal, and hydroelectric energy limits the greenhouse gas emissions from the power sector and hence is a strategy to address global climate change. However, although renewables are preferable to fossil fuel generators from an emissions standpoint, electricity output from renewable sources is intermittent since it is derived from variable natural resources which makes generation unsteady and unreliable and hence presents challenges for grid operators[265].

To ensure a balanced electricity supply and demand on the grid, grid operators should be able to know how much renewable energy is being generated at any instant, how much generation is expected, and how to respond to changing generation and demand which may be difficult to know due to the intermittent nature of renewable energy and the wide variety in terms of size and locations of the energy resources across the grid coverage. As the share of renewable energy capacity grows on the grid, these challenges become complex. [265].

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2.14.4 Grid Integration of Renewable Sources

The two main types of renewable energy generation resources are distributed generation, which consists of small-scale renewables on the distribution side of the grid where electricity load is served; and centralized, utility-scale generation in which larger power plants are connected to the grid through transmission grid[265]. This is illustrated in Figure 2-6.

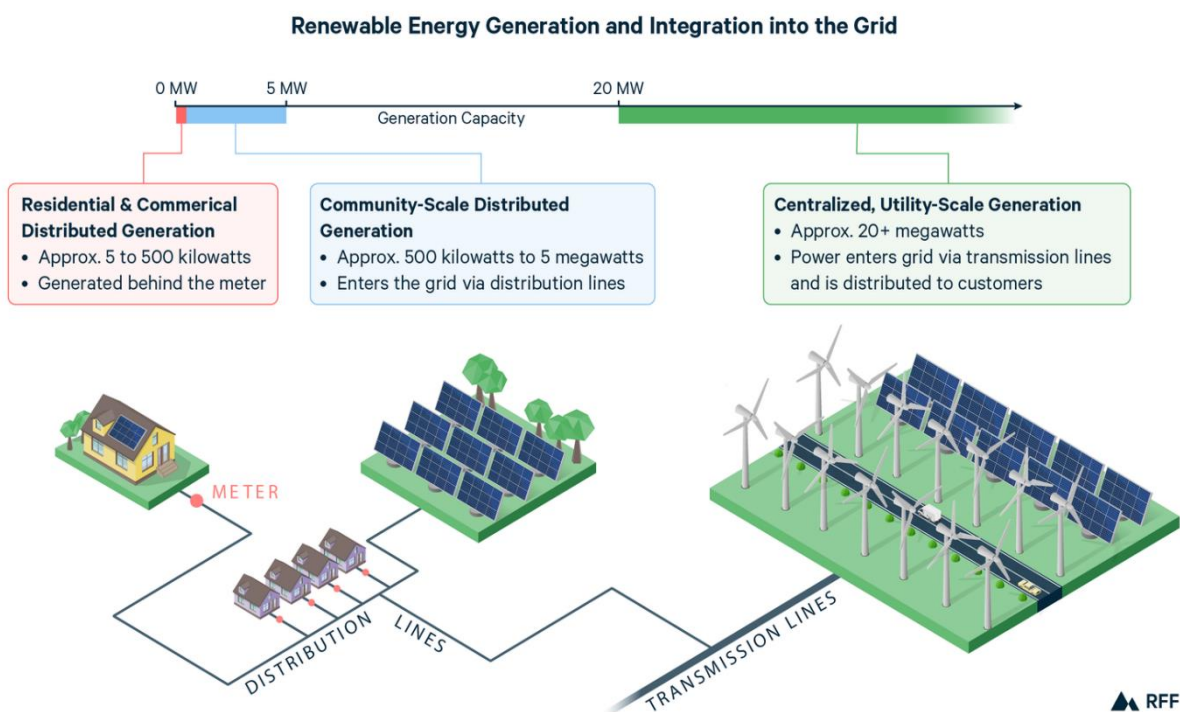


Figure 2-6: Integration of renewable energy generation to the grid

From Figure 2-6, it is noted that renewable energy sources can be integrated into the grid through centralized or decentralized generation.

2.14.4.1 Utility-Scale Generation

The centralized, utility-scale renewable energy power plants are comparable to fossil-fueled power plants and produce large quantities of power just like natural gas, coal, and nuclear power plants, for long distance transmissions to distribution lines to homes and commercial buildings[265]. The difference with renewable power plants like solar and wind is that they are not dispatchable like the conventional fossil-fuel plants and are not able to generate power when called upon due to reliance on variable resources like wind and solar whose availability and supply varies over time. Once available for generation, the renewable energy get priority in the dispatch order since they are the cheapest having no fuel costs)[265]

2.14.4.2 Distributed Generation

The distributed resources include rooftop solar panels, wind turbine generators located on-site at point of use. These sources are connected to the grid through distribution grid network. Distributed sources are small residential and commercial generators often ranging between 5 and 100 kW. Distributing generation often occurs “behind the meter,” meaning the electricity is generated for on-site use by the consumers who are prosumers[2]. The distributed systems are typically designed to lower electricity demand at the source instead of increasing power supply to the grid e.g., when solar is available a house with solar panels does not need electricity from the grid for residential use. Some distributed systems are community-scale renewables, which are larger in size than house-based systems but smaller than utility-scale and are often installed. “in front of the meter,” meaning electricity is not used on-site but rather flows onto the distribution grid to be used by homes and businesses in the vicinity[265].

2.14.4.3 Comparing Generation Types

Economically, centralized utility-scale renewables are much cheaper than distributed resources because of the economies of scale that they enjoy e.g., in 2018, the levelized cost of rooftop solar was about 4.5 to 7 times more expensive per MWh relative to utility-scale solar power systems. The central stations are also much easier to operate and control by the utility than the decentralized systems since the distributed renewables are often small and located behind the meter, making it very difficult to track from a grid operator’s perspective and can significantly complicate load forecasting. The existence of decentralized systems is only noticed by the grid

operators because they noticeably reduce customer demand for electricity at particular times[265].

On the positive side, distributed renewables typically used on-site or nearby, distributed can significantly reduce energy losses incurred during electricity transmission from centralized station thus reducing demand and need for investment in new transmission and distribution infrastructure. Additional benefits are derived by connecting to microgrids since distributed renewables can also provide greater resilience in times of disruptions to the power grid by providing power even if the larger grid experiences outages from disturbances caused [265].

2.14.5 Impact of Renewables on the Grid

The connection of renewable energy generation to the grid impacts how the power plants and energy sources are dispatched. The grid often absorbs electricity from renewable sources when there is sufficient demand for electricity, although cases of excess generation from renewables can still occur and hence the need for production curtailment. Under normal circumstances, only grid operators use the dispatchable sources to make up the difference between demand and supply from renewables known as net load, which is the difference between the forecasted load and generation from renewables on the system[265].

As more renewables are integrated into the grid, intermittent poses challenges to the grid operators mainly in the form of forecasting and meeting load demand. More renewables on the grid make it necessary to forecast parameters like weather which changes quickly and unpredictably. It also requires grid operators to be flexible and quick to respond react to new conditions and generation patterns others. Failure to do so could potential there would be power shortages and blackouts. [265]. To balance grid operations in this system with high penetration of renewables requires a very steep “ramp,” or rapid dispatch of non-renewable energy sources for stability. Grid operators will occasionally reduce the output from, some renewables when generation is higher than demand. [265].

2.14.6 Implications for the Future Grid

The global commitment to reduce greenhouse gas emissions, climate change and falling costs and state policies have combined to create momentum for faster adoption of renewable energy generation. Many states have committed themselves to generate most of their power from renewables e.g., the state of Hawaii has set a target of generating 100% of its electricity from

renewable energy sources by 2045. The modern grid requires a high degree of flexibility on both the demand and supply sides to cope with high penetration of renewables to the grid[265].

- i. The various measures necessary to increase grid flexibility and improve the integration of renewable resources include:
- ii. Use of energy storage paired with variable renewables to accommodate fluctuations in renewable generation so that electricity can be stored during times of high generation for later use during periods of high demand.
- iii. Developing more transmission capacity to connect areas endowed with renewable resources like very sunny or windy areas with areas of high electricity demand to maximize the grid uptake and consumption of renewable resources and reduce uncertainties.
- iv. By optimum combination of different renewable sources to balance out variability of production of one resource with others e.g., interconnecting wind, solar, hydro, geothermal to minimize volatility in production compared to relying exclusively on one source.
- v. Through demand side management to strategically optimize the times when electricity is consumed to reflect the availability of generation with the objective demand-shifting to times of high renewables production for operations like preheating electric hot water heaters or charging electric cars when there is high generation of renewables.
- vi. By placing value on generator flexibility in the wholesale power markets to motivate grid flexibility e.g. establishment of a flexible ramping product which compensates power producers for ability to quickly ramp to manage the “duck curve” through the These encourages the market to decide how to best enable flexibility, instead of prescribing a set solution[265].
- vii. Behind the meter measures which encourages consumers to produce own power and sell excess when prices are favorable

2.15 Smart Energy Systems

Smart energy systems focus on measures like energy efficiency, energy end use savings and sector integration to create energy system flexibility, harvest synergies by applying all

infrastructures and reduce energy storage cost. The Smart Energy System concept is necessary to cost effectively achieve 100% renewable energy systems. The smart energy systems capture the entire energy system to identify suitable energy infrastructure designs and operation strategies, unlike concepts like smart grids which only capture a specific sector like electricity[3, 12, 61].

The most effective and least-cost energy options are established when the electricity sector is combined with other energy applications like cooling, heating, and the transport sector. The combination power and gas infrastructures could play a leading role in design of future renewable energy systems, and the electrification of heating and transport as well as through electro fuels by enabling flexibility and integration of renewables in all sectors. Application of low-temperature district heating, use of renewable energy heat sources heat and heat saving measures, provide a better pathway compared to individual heating solutions Cogeneration is an important driver in the energy transition by eliminating fossil fuels and increasing energy system efficiencies.

Smart energy systems like the Smart grid technology presents unprecedented opportunity to transition the energy industry into an era of high availability, reliability, and efficiency. This will enhance economic and environmental health of both developed and developing world economies[3, 12, 29, 64]. There is need to carry out testing, consumer education, technology improvements, standards development and regulations, and information sharing between energy projects to ensure that the benefits derived from the Smart Grids are realized during the energy transition period[61, 96, 267]. The benefits of smart grid include:

- i. Smart grids enable a more efficient power transmission.
- ii. They facilitate quicker restoration of electricity in case of power supply disturbances.
- iii. Smart grids enable reduction in operations, maintenance, and management costs for electricity utilities, which lowers power costs for consumers.
- iv. Use of smart grids can reduce peak demand which leads to delayed or suspended expansion of capacity leading to reduced or lower electricity rates.
- v. Increased integration of large-scale renewable energy systems

- vi. They facilitate more efficient and better integration of customer-owner power generation systems, including renewable energy systems thus converting electricity consumers of a traditional grid to prosumers.
- vii. There is improved energy security by use of smart grids due to increased decentralization of generation which enables increased use of local energy resources, most of which are renewable sources like wind, solar and biomass.
- viii. Facilitate the integration of renewable energy sources in the electricity network.
- ix. Support or facilitate new uses of electricity, like electrification of transport or development of the electric vehicles.
- x. Facilitate the emergence of innovative energy efficiency solutions at community level like the development of smart cities or smart neighbourhoods[12, 61, 116].

2.16 Energy Transition

As highlighted in section 1.6, the energy transition refers to the pathways undertaken toward global transformation of the energy sector from one dominated fossil fuel by to a zero-carbon energy mix by the second half of this century[3, 21]. An energy transition is a structural change in energy generation, supply and consumption aimed at limiting or halting the global climate change. The world has so far witnessed three typical energy transitions. The first transition involved replacement of wood with coal as the main energy source. In the second transition, oil replaced coal as the dominant energy resource. In the third transition, there is global commitment to replace fossil fuels with renewable energy[2, 3, 58].

The commitment to reduce energy-related greenhouse gas emissions and to limit the global climate change is at the centre of the global energy transition [3]. The impacts of greenhouse gas emissions can be prevented, lessened, and even reversed by firmly committing to renewables and supporting a definitive transition to clean and inexhaustible sources of energy like wind energy, photovoltaic solar energy, solar thermal energy, hydraulic energy etc. It is however not practical to immediately stop using non-renewable energies [36]. The energy transition is the only way forward if we want to achieve the most ambitious objective of the Paris Agreement aimed at limiting the temperature of the planet to 1.5°C above pre-industrial values. According to IPCC, the world should achieve carbon neutrality by 2050. All countries to create a global energy system that is stable, sustainable, and affordable based on renewable

energies and low carbon sources like nuclear [29, 36, 44, 61]. For the transition to remain technically and economically feasible and beneficial, policy initiatives are necessary to steer the global electricity transition towards a sustainable energy and electricity system and facilitating conversion technologies and availability of sustainable energy resources[3, 29, 44].

At the heart of the energy transition is the commitment to reduce energy-related greenhouse gas emissions and to limit the global climate change[3]. Decarbonisation of the energy sector is an urgent global scale action, with more action needed to reduce carbon emissions and mitigate the effects of global climate change. Among other measures, the use of renewable energy and energy efficiency measures can realise as high as 90% of carbon emission reductions[24]. A sustainable energy transition will be facilitated by advances and application of information technology, use of smart technology, facilitating legal and policy frameworks and energy/electricity market instruments.

Energy transition is the change in global energy sector from fossil-based systems of energy production and consumption to renewable energy sources like wind and solar. Measures applied in the transition include higher penetration of renewable energy into the energy supply mix, electrification of key sectors and improvements in energy storage. Energy transition refers to the pathways used to transform the world energy systems from fossil-based to zero-carbon by the second half of this century. The objective of the energy transition is to reduce anthropogenic greenhouse gas emissions most of which are associated with the energy sector dominated by fossil fuels. The shift from nonrenewable energy to renewable energy is made possible by advances in technology and the push by society towards sustainability. The energy transition seeks to reduce energy-related greenhouse gas emissions through different decarbonization measures[3]. The cost renewable energy sources like wind and solar have dropped significantly making them cost competitive with traditional high-carbon energy resources positioning them to play a leading role in the transition[12, 61].

It is estimated that the use of renewable energy and application of energy efficiency technologies and measures can reduce the carbon emissions by up to 90% of targeted reductions[3, 24]. The energy transition will greatly be facilitated by information technology, smart technology and smart energy systems, policy measures, market instruments and effective planning and optimization models[21, 25]. Therefore, the energy transition

represents changes in the energy systems in terms of energy supply, processing, or production, energy conversion and delivery, energy consumption, energy markets. The energy transition has implications on the economy, society, environment, institutions and technology [24, 25]. The transition should therefore be assessed within all the important dimensions[12, 230].

About 66% of the entire global electricity generation is derived fossil fuel sources, namely coal, natural gas, diesel and heavy fuel while 79% of the global total generation is derived from non-renewable energy sources i.e. fossil fuel and nuclear energy[268]. These non-renewable sources work on thermodynamic cycles namely the Rankine cycle for nuclear and coal, diesel cycles for direct combustion generation like diesel and natural gas and the Brayton cycle for gas turbine power plant. These thermodynamic cycles have average efficiency of 35%[269] meaning over 65% of fuel energy is wasted and they account for the bulk of greenhouse gas emissions from power generation[269]. The global energy related carbon emissions were 33.2 giga-tonnes (Gt), following two years of increases [268]. Figure 2-7., shows the relative contribution of energy sources to global greenhouse gas emissions.

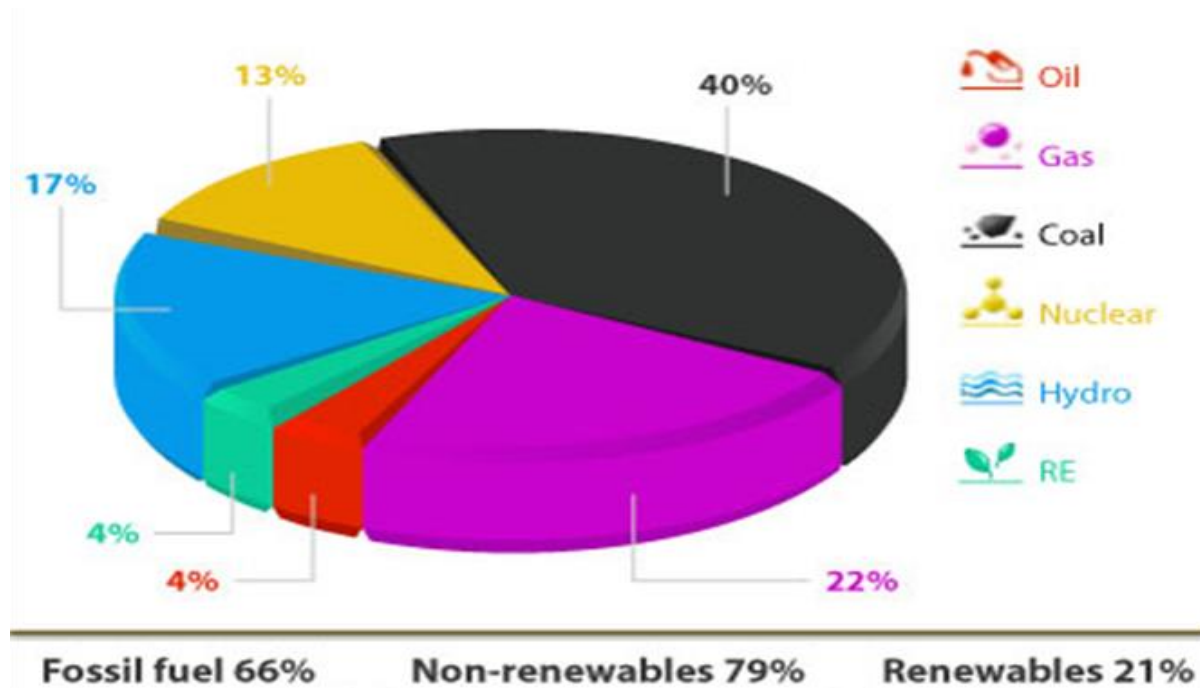


Figure 2-7: Global greenhouse gas emissions by energy sources

From Figure 2-7., it is noted that 79% of global electricity in 2019, came from non-renewable sources, then 17% was generated by hydropower while 4% was supplied by wind, solar and other renewables combined. It should be noted that about 40% of the cost of building a Hydro dam is spent on burning fossil fuels to diesel-powered heavy machinery, moving earth, making reinforcing steel, producing concrete, building turbines and running the heavy machinery used to build those dams [268]. This is evidence of global overreliance on fossil fuels. In South Africa as an example, the electricity supply is dominated by coal fired power plants which supply about 70% followed by oil at 21% while renewable sources and the rest account for just 9% of the remaining total generation[52].

The core of the transition to a sustainable energy future is a decarbonised electricity power sector that is dominated by renewable energy sources. For this reason, the share of renewable energy in the power sector is expected to increase from 25% in 2017 to 85% by 2050 with wind and solar playing a key role in this transition. To realise this transformation, new approaches new approaches are needed in to power system planning, new energy sources and technologies, new approaches system and market operations, and regulation and public policy initiatives[3]. There will be need to double the share of electricity in end use applications from about 20% in 2015 to 40% in 2050 as low-carbon electricity transforms into the main energy carrier. With the transport sector and district heating being significant contributors to the greenhouse gas emissions, the electric vehicles (EVs) and heat pumps would become more the new order in many parts of the world. Overall, renewable electricity should carter for about 60% of total renewable energy use the in terms of final energy use which is about two and a half times the contribution in 2017[2, 27].

The energy transition is an expensive endeavour with additional costs of detailed and comprehensive, long-term energy transition costing an estimated USD (United States Dollars) 1.7 trillion annually to 2050. However, expected savings accruing from reduced air pollution, low environmental damage, and better health which can outweigh these huge costs. Additionally, the energy transition will significantly improve the global socio-economic footprint of the energy system when compared to the business-as-usual (BAU) case scenario, which will lead to improved global welfare, higher GDP (Gross Domestic Product) and higher access to employment opportunities. The expected cumulative gain through increased GDP from 2018 until 2050 will be about USD 52 trillion. The planned energy transition calls for

substantial additional investment in low-carbon technologies compared to existing plans and policies[27].

One of the greatest challenges facing humanity today is to meet the ever growing energy demand in an environmentally benign and sustainable manner [21, 270]. Fossil fuels like coal, oil and gas remain vast or abundant in supply while for some like coal will remain the cheapest form of energy for many years to come, and therefore will remain attractive and competitive[20]. The global climate has been changing, with serious consequences already experience and with more expected to come[51]. These consequences include.

- i. The surface temperature has increased by about 0.6oC over the 20th century.
- ii. Snow cover and ice extend has decreased by 10% since 1960.
- iii. The atmospheric concentration of carbon dioxide has increased by about 31% since 1750.
- iv. Three quarters (3/4) of all anthropogenic emissions of carbon dioxide over the last two decades come from fossil fuel combustion.
- v. Increasing cases of destructive windstorms and hurricanes[271]
- vi. The sea level is projected to rise by 0.09 to 0.88 m between 1990 and 2100 due to a combination of thermal expansion and loss of ice caps [51]
- vii. El Niño events which are rainfall patterns which lead to floods and drought particularly in the tropical and semi-tropical areas are influenced by the surface temperature of the oceans around the world, and more so the pattern of ocean surface temperature in the Pacific off the coast of South America [271]

The world had witnessed a massive energy transition from reliance on almost entirely renewable sources in form of biomass energy to an energy mix dominated by fossil fuels between 1800s and 2000s [272]. According to [21] the global primary energy use in the year 1800 was about just about 20.35 EJ (exajoule = 1,018 joule), of which about 20 EJ was fuel wood and the rest from coal. In Figure 2.8. below, it is shown how primary energy use has grown since 1800, with significant contribution from fossil fuels more so between 1950 in 2016 where consumption grew from about 120 EJ to 576 EJ [47].

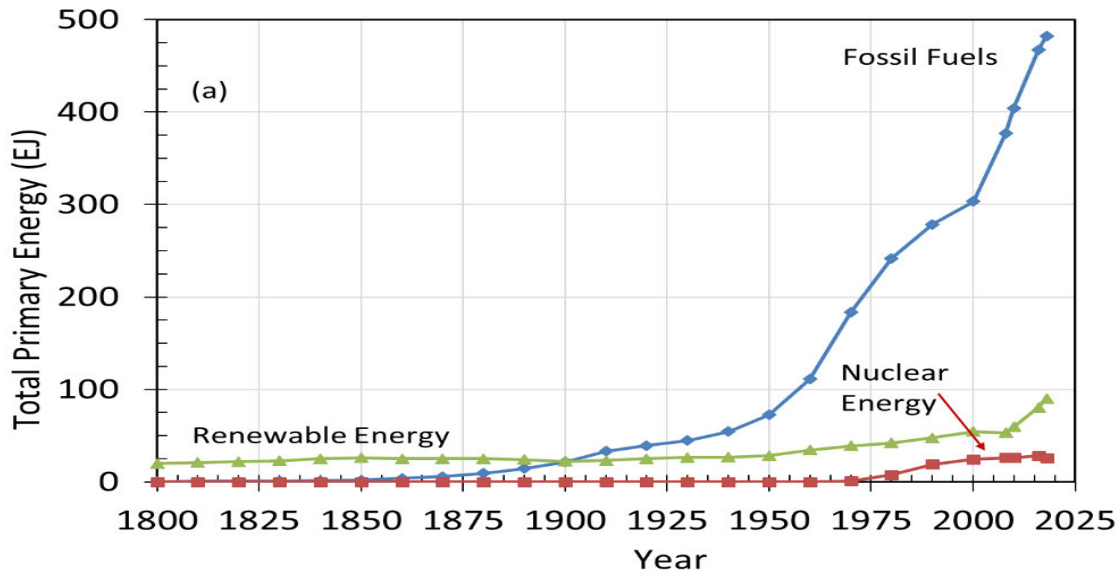


Figure 2-8: Global Primary Energy Use Contribution, 1800–2018 in EJ [272]

From Figure 2-8, it is noted that the global energy-related CO₂ has been growing due to ever growing energy demand. The emissions grew by 1.7% to a historic high of 33.1 Gt CO₂ driven by higher energy demand in 2018. This growth of 560 Mt was the highest rate of growth since 2013, and 70% higher than the average increase since 2010. The emissions from all fossil fuels increased with power sector accounting for nearly two-thirds of emissions growth [47, 273]. Electrical Power Systems globally are faced with the challenge of with greenhouse gas emission reduction policies with integration of renewable energy sources of electricity. According to the Renewable Energy Policy Network for the 21st Century (2017), the global renewable power capacity reached 2,017 GW at the end of 2016 with most of coming from fossil fuels. There is need to maximize power generation from renewables is because they are sustainable and very useful for reduction of greenhouse gas emissions and hence global warming mitigation[274]. However, electricity from renewable sources is characterised by randomness, unregulated supply and is highly unpredictable and unreliable [21]

2.17 . Electrification and its Impact of Emissions

The electrification of machines and operations that currently use fossil fuels for their energy source is one of the sustainable energy options. Available electrification options include s electric cars, electric cooktops, and electric heat pumps. However, to reduce dependence on

fossil fuels and transfer to electric machines, needs electricity from clean and renewable sources[2, 16].

There are various consequences of electrification of electricity. Effective use of electricity from renewable sources, requires the building of more high voltage transmission lines. Electrification also requires that the quantity of electricity to the grid must increase to accommodate the increase in demand[2, 61].

2.18. Chapter Summary and Discussion

Through the cumulative effect of the Stockholm, Rio, and Johannesburg conferences, sustainable energy development (SED) was identified as a key requirement for sustainable development and so energy was linked energy to the environmental dimension in the Stockholm conference, economy in the Rio conference and society in the Johannesburg conference. Sustainable development is expected to bring economic and progress in an environmentally benign manner free from wastage, pollution, destructive emissions and social strife in a facilitating political environment. Sustainable development has got three main dimensions of economic, social, and environmental aspects while sustainable energy has got two additional dimensions of technical and institutional or political environment.

2.19. Energy Sustainability Measures

Various sectors have different opportunities to exploit to ensure sustainability in resource applications. They are listed as follows.

- i. Energy sector: Transition from fossil fuels, nuclear, energy, renewable energy, smart grids, energy efficiency measures
- ii. Agriculture: Use of bio wastes for energy, bio fertilizers, and other green practices like use of green manure from biogas digesters.
- iii. Buildings: Use biogas/biomethane and consumers to be converted to prosumers with grid modernization, as well as energy conservation measures.
- iv. Transportation: Electrification of transport, use of biofuels, energy efficiency, use of hydrogen energy[2, 3].

2.20. Characteristics of Sustainable Energy

The following are the characteristic features of sustainable energy.

- i. For energy sources and systems to contribute to sustainable development, they should possess the following characteristics.
- ii. Energy resources and systems are sustainable if they are renewable or perpetual in nature.
- iii. Sustainable energy systems should not be wasteful but efficiently produced and used with minimum resource wastage.
- iv. Sustainable energy and energy systems should be economically and financially viable.
- v. Energy is sustainable if the source is secure and diverse.
- vi. Sustainable energy and energy systems should be equitable or readily accessible, available, and affordable.
- vii. Sustainable energy development should bring positive social impacts.
- viii. Sustainable energy should be associated with minimal environmental impacts[57, 100, 275].

2.21. Greenhouse Gases

The composition of global atmospheric greenhouse sources and their sources is summarised in Table 2-1.

Table 2-1: Global greenhouse gases, sources, and effects

% Comp.	Greenhouse Gas	Description	Effect and Control Measures
76	Carbon dioxide (CO ₂)	Carbon dioxide (CO ₂) is a greenhouse gas with the ability to absorb and radiate thermal energy whose main source is fossil combustion. Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance that is causing	This can only be realized by minimizing the consumption of fossil fuels particularly in electricity generation and transport industries through substitution with renewable energy

		Earth's temperature to rise.	sources and electrification of transport among other measures.
16	Methane (CH ₄)	Emitted by natural and artificial processes like anaerobic digestion and during the production and transport of fossil fuels like coal, natural gas, and oil. Therefore, methane is added to the atmosphere through natural and anthropogenic sources. 30% of the methane flux originates from natural sources while about 70% is contributed by anthropogenic source	Controlled biodegradation through anaerobic digestion and use of clean fuels is the best strategy to limit methane emissions.
6	Nitrous oxide (N ₂ O)	Food production, particularly the use of fertilizers, is the primary source of N ₂ O emissions. As well as fossil fuel combustion in power generation, industry, and transportation as a product of combustion and wastewater treatment process.	Measures to limit Nitrous oxide (N ₂ O) emissions include use of cleaner and renewable fuels, controlled combustion of fuels and exhaust gas cleaning measures among others
2	F Gases	The F gases result from industrial processes, refrigeration systems, and the use of some consumer products associated with emissions of F-gases. These gases include hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur	The main negative impact of Sulphur hexafluoride (SF ₆) is that is highly potent and has intense absorption at 10.3 μm (969 cm ⁻¹) in the atmospheric window

hexafluoride (SF ₆)	region and while it has atmospheric lifetime of 3200 years

From Table 2-1, it is observed that the main greenhouse gas emissions from anthropogenic sources are F Gases, with about 2% atmospheric composition, Nitrous oxide (N₂O) with about 6% concentration, Methane (CH₄) with about 16% concentration and Carbon dioxide (CO₂) which has got the highest atmospheric composition of about 76%.

2.22. Emissions by Sector and Mitigation Measures

Various economic sectors have different contributions to the global greenhouse gas emissions as summarised in Table 2-2.

Table 2-2: Contribution of greenhouse gas emissions by sector

Economic Sector				% Share of Emissions	Description
1	Electricity and heat production			25	Greenhouse gas emissions came from electricity and heat production which include coal combustion, natural gas, and oil combustion for electricity and heat application. This constitutes the highest single source of global greenhouse gas emission. This percentage can be reduced through options like cogeneration for own power generation, shift to renewal energy sources and energy generation and conservation efficiency

2	Industry	21	Emissions came from industrial operations with onsite facilities for energy production mostly involving fossil fuels like coal, gas, and petroleum products like diesel
3	Agriculture, Forestry, and Other Land Use	24	Greenhouse gases are emitted from agricultural activities like crop cultivation, livestock farming activities and agricultural related deforestation. However, on the positive note, carbon dioxide is removed from the atmosphere by sequestering carbon in biomass through photosynthesis
4	Transportation	14	The main sources are transportation activities on road, rail, air, and marine transportation. About 95% of the 14% emissions from transportation energy came from petroleum-based fuels, inform of petrol, gasoline, and diesel. Measures to limit these emissions include use of electricity from renewable sources in traction e.g., rail, increased use of biofuels and other renewable energy fuels and investment in fuel efficiency measures
5	Buildings	06	Main building sector activities responsible include onsite power generation, burning fuels for heat in buildings, or cooking and other energy consuming activities. On the positive side buildings can significantly reduce this load by own generation from renewable sources, energy savings and decentralized grid generation for grid supply

6	Others	10	About 10% global emissions come from energy sector related sources other than heat and electricity production like fuel extraction, extraction and refining, processing, and stationary automotive engine application. Energy economics and efficiency applications in consumption and use of renewable energy sources can reduce this type of emission

From Table 2-2, it is noted that electricity and heat production have the highest contribution to global greenhouse gas emissions by economic sector. Others in the order of their contributions are agriculture, forestry, and other land use, industry, transportation, and buildings.

This chapter demonstrated that carbon dioxide has the highest atmospheric composition of greenhouse gases followed by methane, Nitrous oxide (N₂O) and F gases. Electricity and heat production and energy related upstream and downstream operations are the largest sources of greenhouse gas emissions followed by the agriculture, forest, and land related activities. Other leading sources of greenhouse gas emissions are the industry, transportation, and the buildings sector. Global electricity generation remains dominated by fossil fuels with renewable energy sources contributing a smaller proportion. Sustainable development needs sustainable energy which should be reliable, stable, good quality, affordable non-polluting and socially acceptable. Whereas sustainable development has social, economic, and environmental pillars, sustainability of energy and electricity generation systems are assessed by a five-dimensional approach consisting of environmental, economic, social, technical, and institutional sustainability as a strong measure of resource and system sustainability.

Various measures can be put in place to limit emissions from various sectors. New efficient technologies should be developed and exploited for to maximize use of abundant but intermittent renewable sources a sustainable mix with limited non-renewable sources optimized to minimize cost and environmental impact but maintained quality, stability, and

flexibility of an electricity supply system. Other measures that can limit emissions include electrification of transport and industrial activities with electricity coming from renewable and low carbon sources.

2.23. Energy Sources for power Generation

The world has various energy sources that can be harnessed for power generation with different impacts. These sources consist of both renewable and non renewable sources. Examples of potential energy sources for power generation are;

2.23.1. Coal

The Russia's 2022 incursion into Ukraine has led to stumbling of the steady global net phaseout of coal for electricity and industrial production by forcing the European Union (EU) nations to return to coal. Coal demand has also grown in some Asian and African nations. Coal is the largest contributor to global electricity generation and hence greenhouse gas emissions. Therefore a transition from coal to hydrocarbons is seen as a shift from lesser to superior fuels. Physically, hydrocarbons are considered superior to coal due to their higher energy densities, their economic and energetic efficiencies compared to coal. **In order** to achieve the goal adopted at COP28 of net zero emissions of greenhouse gases from the energy sector in power generation. With coal accounting for over one-third of global power supply, the scale of the task cannot be overstated since coal is the most carbon-intensive fuel, and is responsible for over 40% of all energy sector CO₂ emissions. Projections show that if coal power plants and industries continue to operate the way they do today would “lock in” emissions which will push the world well beyond the 1.5 °C limit [276].

Despite the rapid growth in renewables-based power generation globally, the coal demand grew in the year 2023 with most of the growth taking place in the People's Republic of China then India and other emerging and developing economies. Since 2018, all demand in coal growth was mainly for power generation and accounted for nearly all the increase in global CO₂ emissions since 2019. According to the latest IEA estimates, clean energy deployment since 2019 has helped to avoid coal demand of around 580 million tonnes of coal equivalent per year on average – equivalent to the coal demand for power generation of Indonesia and India combined. Many countries have adopted net zero emissions pledges, that call for the

phasing out the unabated use of coal and other fossil fuels, with the pledges accounting for more than 85% of global energy sector emissions [276].

2.23.2. Geothermal energy

Geothermal energy refers to the heat from the earth and the word geothermal is derived from two greek words, Geo meaning earth and thermal meaning heat. Geothermal energy resources are reservoirs of hot water either naturally existing or are human made at varying temperatures and depths below the earth's surface. Geothermal energy is generated from the original formation of the planet and the radioactive decay of materials stored in **rocks and fluids** in the centre of the earth. Continuous conduction of thermal energy is driven by thermal gradient existing between the earth's core and the surface. With high temperatures of over 4000°C, some of the rock in the centre of the Earth melts and form hot molten rocks called magma.

The high temperature of the mantle makes it to behave plastically and causes portions of the lighter mantle to convect upwards, since it is lighter than the surrounding rock. In the core, the rock and water in the Earth's crust can reach 370°C and in some places, the thermal energy in rocks and fluids can be found from shallow depths below the Earth's surface. Geothermal energy resources may be exploited from naturally occurring heat, rock and water permeability or through enhanced geothermal systems, which create geothermal resources through hydraulic stimulation. The first recorded case of geothermal electricity production was in Larderello, Italy in 1904, but geothermal heat has been used for applications like bathing since the Palaeolithic Age

2.23.3. Hydrogen

Hydrogen is this one of the simplest and most abundant elements on the planet earth combining readily with other chemical elements, and found as part of another substance, like water, hydrocarbon, or alcohol as well as in natural biomass like plants and animals hence considered as an energy carrier and not energy source. The global annual production of hydrogen is about 55 million tons with increasing consumption growing at about 6% per year. About 50% of the global demand for hydrogen is met by steam reforming of natural gas, about

30% from oil/naphtha reforming from refinery/chemical industrial off-gases, 18% from coal gasification, 3.9% from water electrolysis, and 0.1% from other sources. Although electrolytic and plasma processes show high efficiency for hydrogen production, the processes are energy intensive processes[277].

Hydrogen is a clean energy carrier that with potential applications in power generation, automotive application as transportation fuel, fuel for industrial boilers, and even for commercial and residential heating. Since most of the hydrogen is produced currently is from catalytic steam reforming of natural gas, which is fossil there is growing need for use of renewable materials [278]. The utilisation of hydrogen is concentrated in four principal areas of industry, electricity, transport and building heating. It is also used as industrial raw materials, used as a means of energy storage and alternative fuels for transport and power generation.[7]. It is desirable to have a regional electricity-hydrogen integrated energy system that couples electricity and hydrogen to improve renewable energy utilization and a double layer mixed integer planning model aimed at reducing the levelized cost of hydrogen by optimizing the proportion of wind and photovoltaic power generation installed in the system and the electricity purchased via the grid. An integrated expansion plan for electricity, natural gas, and hydrogen systems can contribute to the decarbonization of energy systems and identify a mix of technologies that meet energy demands and emissions with optimal economics[7, 279].

The transition towards a carbon-neutral future relies on renewable hydrogen because of its spatio-temporal storage and sector coupling potential, which makes it identifies as an energy vector. However, hydrogen's large-scale deployment faces many unresolved issues like least-cost production challenges, optimal facility siting, and overall implications on power and energy systems. Expansion planning provides an opportunity to analyze the various issues in the holistic context of energy systems[6, 280]. Energy sustainability can be improved by using hydrogen for energy related applications to substitute fossil fuels. The common methods for hydrogen production are electrolysis or methane reforming (SMR) and autothermal reforming (ATR) for syngas production [281]. The technologies can use biomethane, as a substitute natural gas to provide a lower carbon and renewable hydrogen for transport and power generation. Use of biomethane also provides a hedge against growing demand for fossil fuels particularly the natural gas and hence play a leading role in the energy transition.[113, 282]

2.23.4. Hydropower

Hydropower, also called hydroelectric power, is one of the oldest and largest sources of renewable energy, that utilizes the natural flow of moving water to generate energy. In hydropower exploitation, a dam or diversion structure is developed to change the natural flow of water. Hydropower, or hydroelectric power, is a renewable source of energy that generates power by using a dam or diversion structure to alter the natural flow of a river or other body.

2.23.5. Petroleum sources

Petroleum, which is also referred to as crude oil, or simply oil, is a naturally occurring fossil fuel which is a yellowish-black liquid mixture of mainly hydrocarbons, found in geological formations. The name petroleum includes naturally occurring unprocessed crude oil and petroleum products that consist of refined crude oil. Upon refining, hydrocarbon of different properties are used as sources of energy e.g. petrol, diesel, heavy fuel oil and industrial diesel oil.

2.23.6. Natural gas

Natural gas is a fossil fuel with lower carbon footprint compared to other traditional sources, like coal and oil and hence can play a supporting role in the energy transition. Natural gas is flexible in use which makes it possible to integrate effectively with renewables. Whereas the global energy transition is underway, a shift from fossil fuels to renewables will take some time.

According to the International Energy Agency, switching from coal to natural will reduce CO₂ emissions by up to 40% per unit of energy output. The emissions from natural gas can be reduced further by using carbon capture, utilization, and storage (CCUS) technologies and by preventing methane leaks. There has been a shift from coal to natural gas in some parts of the world to reduce emissions and air pollution in the short term and middle term. Therefore natural gas can be used as a bridge a bridge to more sustainable energy sources because it is a “cleaner” alternative to other fossil fuels and can aid in the energy transition. However, the concern is that natural gas still creates emissions and will only prolong a transition to renewables, therefore natural gas is a “bad bridge” that create stranded investment in new

fossil fuel infrastructure, although it is a good backup for renewable-based power systems[30, 113, 283, 284].

2.23.7. Wind energy

Wind energy is possessed by moving air caused by differences in temperature and hence density over different parts of the earth. Wind energy is exploited by wind turbines for power generation or other mechanical applications like milling. In wind turbines, wind rotates the turbine rotor blades converting the kinetic energy into rotational energy which is transferred by a shaft coupled to an electric generator. Wind can produce electricity by converting the kinetic energy of air in motion into electricity.

Wind energy costs have reduced due to improvement in technology and scaled up as well as capacity factors have risen e.g. between 2010 and 2020, the global weighted-average levelised cost of electricity (LCOE) of onshore wind reduced by 56%, from USD 0.089/kWh to USD 0.039/kWh. While over the same period, the LCOE of newly commissioned offshore wind projects reduced by 48%, while wind turbine capacity has also increased from about 0.05 MW in 1985 and a rotor diameter of 15 metres to turbine capacity of 3-4 MW range onshore and 8-12 MW offshore today.

Wind turbines first emerged more than a century ago but following the invention of the electric generator in the 1830s, successful attempts were made to harness wind energy to produce electricity which first took place in the USA and UK between 1887 and 1888. However, modern wind power sector emerged in the 1980s with a modern wind power systems being first developed in Denmark, where horizontal-axis wind turbines were built in 1891 while a 22.8 metre wind turbine began operation in 1897..

2.23.8. Solar energy

Solar energy is increasingly getting popular for power generation, heating and desalinating water as main applications. Solar photovoltaic (PV) which uses electronic devices or called solar cells, to convert sunlight directly into electricity and solar thermal are two modes of solar power generation.

2.23.7.1 Solar PV

The PV solar system enables significant reduction in emissions as compared fossil fuels and has a rather widespread social propensity in particularly when used to offset energy consumption costs. Solar PV has increasingly become more popular partly because of the policies that impact on economic sphere and beyond. An important factor to make better use of the investment for installing solar PV system is the self-consumption and sell of excess power to the grid by converting consumers to prosumers.

2.23.7.2. Solar CSP

Concentrated solar power (CSP, also known as concentrating solar power, concentrated solar thermal) systems are used to generate solar power by using mirrors or lenses to for concentrating a large area of sunlight into a receiver. Power is generated by use of a heat engine usually a a team turbine connected to an electrical power generator or by powering a thermochemical reaction. The global installed capacity of concentrated solar power stood at 6.8 GW in 2023. A CSP plant may incorporate thermal energy storage, for energy storage either in the form of sensible heat or as latent heat using molten salt which enables these plants to continue generating day and night [285].

2.23.7.3. CSP Versus Solar PV

Concentrating Solar Power (CSP) technologies apply mirrors to concentrate solar radiations and convert it into heat for steam generation needed to drive a steam turbine coupled to a team generator for power generation. Concentrating solar power is a complementary technology to photoltaic (PV). That applies concentrating collectors to generate high temperature heat to a conventional power cycle which can integrate efficient and low-cost thermal energy storage technologies to enable power generation according to the demand profile. The CSP systems can avoid “shadow plant capacity” needed to secure generation capacity in periods lacking sunshine or wind, and can supply grid services, black start capabilitie needed to support higher penetration intermittent renewable sources and avoids a high share of expensive electric storage technology in the grid systems [285].

2.23.9. Nuclear energy

Nuclear energy can be used for power generation but must first be released from the radioactive atom through nuclear fission which splits atoms to release heat energy in a nuclear reactor. A nuclear reactor, or power plant, is designed to control nuclear fission to for electricity generation.

Proponents of nuclear power argue that nuclear power is a safe, sustainable energy source that reduces carbon emissions because nuclear energy and power generation has the lowest levels of fatalities per unit of energy produced as compared to other energy sources like coal, petroleum, natural gas and hydroelectricity arising from air pollution and accidents [286].

Nuclear energy has ability to provide low-emission, dispatchable and flexible power to the electricity system. Through carbon pricing, an explicit value is placed on the low emissions benefits of nuclear power. Nuclear energy designs should adequately remunerate the capacity and ancillary services that nuclear energy is able to provide. In some countries, these costs are embedded in their marginal cost of electricity. Capacity mechanisms can be used to remunerate power generators for availing electricity generation capacity as applied in the US and some EU countries like France and the United Kingdom[287].

2.23.10. Ocean thermal Energy

Ocean Thermal Energy which is also called Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology which exploits the temperature difference between the warm surface waters of the ocean and the cold depths to for power generation. It is a clean energy generation having a potential to supply a consistent and sustainable source of energy particularly in tropical regions with access to deep ocean water [288]. Thermal Energy Conversion (OTEC), utilises the temperature difference between the cold deep parts of the sea, and the warm shallow parts of the sea, to run a heat engine and produce useful work. The deeper parts of the ocean remain cooler since the heat of sunlight cannot penetrate very deep into the water. The greater the temperature difference, the greater the efficiency of the OTEC system. The thermal gradient in the oceans between the deep and shallow parts is maximum in the tropics, 20° C to 25° C since tropics receive a lot of sunlight. The Thermal Energy Conversion (OTEC) systems utilise at least 20° C temperature difference to power a turbine for electricity generation [289] .

In the OTEC system warm surface water is pumped through an evaporator that has a working fluid which vaporizes to drive a turbine/generator. The TEC technology is viable in equatorial areas of the earth having year round temperature differential between the deep cold and warm surface ocean waters of greater than 20 °C (36 °F). The system continuously needs large quantities of both warm and cold water to produce sufficient electricity with projections shwing that a 100 megawatt (MW) OTEC facility requires 10-20 billion of gallons of water per day [289] .

2.23.11. Wave energy

Wave energy exploiattion involves the technologies that capture the movement of ocean and sea waves, and use them to produce energy usually in the form of electricity. Energy produced depends on the speed, height and frequency of the wave, and water density. Wave electricity is produced by harnessing the up-and-down motion of ocean waves and is typically produced by floating turbine platforms or buoys which rise and fall with the swells[289].

The wave energy technology captures the kinetic energy in sea or ocean waves by utilising wave energy converters (WECs). Several devices suitable for location in the nearshore and offshore environment are developed for exploitation of wave energy, but all wave energy converters (WECs) generally consist of a sub-surface component (moorings, lines, anchors, foundation) while some have a surface or above surface component. WECs can operate as a single device or an array of devices based on technology applied with a range of devices being tested currently and but the technology remains novel [289]. Examples of design types of designs of wave energy converters include the following:

- i.) Attenuator
- ii.) Point Absorber
- iii.) Over-topping Device
- iv.) Oscillating Water Column
- v.) Submerged Pressure Differential
- vi.) Oscillating Wave Surge Converter
- vii.) Water Pressure/ Bulge Systems
- viii.) Rotating Mass Point Absorber

2.23.12. Tidal energy

Tidal energy makes use of the kinetic energy of the free movement of water caused by tides to produce electricity. The tides are driven by the relative movement of the earth, moon and sun and are easily predicted years in advance. The tidal range which is the difference between the largest and smallest tidal heights is greatest during spring tides, and smallest during neap tides. Tidal energy is exploited by Tidal Stream or Tidal Barrage technologies. The tidal stream Tidal energy converter (TEC) devices are strategically located to capture the kinetic energy of water movement. The tidal barrage is a barrier with integrated turbines is constructed transecting the body of water particularly at an estuary or man made basin which that captures the motion of water as the tide rises and fall [289].

2.23.13. Biomass Energy

Biomass refers to renewable organic material from living organisms i.e. plants and animal which normally contain stored chemical energy from the sun made by plants through photosynthesis. Biomass can be converted to energy by combustion to produce heat and light or

it can be converted to combustible liquids and gaseous fuels through various biochemical processes anaerobic digestion. Biomass feedstock come in the form of dedicated energy crops, forestry residue, agricultural crop residues, algae, wood processing residues, municipal waste, and wet waste like crop wastes, forest residues, purpose-grown grasses, woody energy crops, algae, industrial wastes, sorted municipal solid waste [MSW], urban wood waste, and food waste) [289].

2.23.13.1. Dedicated Energy Crops

These are mainly non-food crops grown preferably on marginal land specifically as biomass. Dedicated energy crops can be herbaceous energy crops which are perennial living for more than two years like switchgrass, miscanthus, bamboo, sweet sorghum, tall fescue, kochia, wheatgrass, and others or short-rotation woody crops which are fast-growing hardwood trees harvested within 5 to 8 years of planting like hybrid poplar, hybrid willow, silver maple, eastern cottonwood, green ash, black walnut, sweetgum, and sycamore. Many of the energy crops can help improve water and soil quality, improve wildlife habitat relative to annual crops, diversify sources of income, and improve overall farm productivity [289].

2.23.13.2. Agricultural Crop Residue

There are significant opportunities to leverage agricultural resources on existing lands without interfering with food, feed, fiber, or forest products. Agricultural crop residues like stalks and leaves, are abundant, diverse, and widely distributed in many parts of the globe e.g. corn stover i.e. stalks, leaves, husks, and cobs, wheat straw, oat straw, barley straw, sorghum stubble, and rice straw. Selling these residues to a local biorefinery additionally provides an opportunity for farmers to generate additional revenue streams [289].

2.23.13.3. Forestry Residues

There are two categories of forest biomass feedstocks: forest residues left after logging timber which includes limbs, tops, and culled trees and tree components that would be otherwise unmerchantable or whole-tree biomass that is harvested specifically for biomass use. Trees that are dead, diseased, poorly formed, and other unmerchantable trees that are often left in the woods after timber harvest can be collected for use in bioenergy, while leaving behind sufficient quantities for habitat maintenance e.g. proper nutrient and hydrologic features. It is

also possible to use excess biomass on millions of acres of forests for energy production and use. The benefit of harvesting excessive woody biomass is reduced risk of fire and pests, as and it also aids in forest restoration, productivity, vitality, and resilience. Therefore biomass can be harvested for bioenergy without negatively impacting the health and stability of forest ecological structure and function[289].

2.23.13.4. Algae

Algae refers to a diverse group of highly productive organisms including microalgae, macroalgae (seaweed), and cyanobacteria or “blue-green algae” used feedstocks for bioenergy. Most algae use sunlight and nutrients to produce biomass containing key components like lipids, proteins, and carbohydrates that are easy convert and upgrade to a variety of biofuels and products. Algae can grow by using fresh, saline, or brackish water from surface water sources, groundwater, or seawater depending on the strain of algae. Algae can also grow in water from second-use sources, like treated industrial wastewater; municipal, agricultural, or aquaculture wastewater; or produced water generated from oil and gas drilling operations [289].

2.23.13.5. Wood Processing Residues

Wood processing produces multiple products and waste streams collectively called wood processing residues and have significant energy potential for potential utilisation. Pulp and paper production leads to significant unused sawdust, bark, branches, and leaves/needles. Which can be conveniently be exploited for energy production as biofuels or bioproducts at the point of processing, for relatively inexpensive biomass for energy applications [289].

2.23.13.6. Sorted Municipal Waste

Municipal solid waste (MSW) include mixture of commercial and residential garbage like yard trimmings, paper and paperboard, rubber, plastics, leather, textiles, and food wastes. Use of MSW for bioenergy also provides an opportunity for reduction of residential and commercial waste by diverting huge volumes from landfills for use in energy generation[290]

2.23.13.7. Wet Waste

Examples of wet waste feedstocks include commercial, institutional, and residential food wastes mainly disposed of in landfills; organic-rich biosolids like treated sewage sludge from municipal wastewater; manure slurries; industrial organic wastes coming from industrial operations; and biogas derived from any of the above feedstock streams. By utilizing these as energy helps create additional revenue for rural economies which solves waste-disposal problems [289].

2.23.14. Biogas

Biogas a renewable energy resource produced by anaerobic digestion of organic feedstock. Biogas is a mixture of gases namely methane, carbon dioxide and traces of other gases and has potential applications in power generation and thermal applications like cooking. Biogas offers a sustainable way to meet the energy needs of the community energy needs, particularly in areas with no access to national grids or where there is a large requirement for heat that cannot be met by renewable electricity. Biogas reduces reliance on solid biomass like wood fuel for cooking, improves health and economic outcomes [31, 291].

Biogas technology is a well-established process for energy generation, nutrient recovery, and valorization of organic residues. The heat value of biogas can be enhanced by biogas cleaning and upgrading making biogas as an alternative to natural gas, while placing biogas sector as a keystone in circular bio-based economy. [292]

Biogas may be used directly or can be modified for extended applications for electricity generation, heat or for transport through biogas upgradation, fuel cell techniques, and conversion to liquid fuels. Biogas application may vary with available quantities which include use of biogas stoves designed consume biogas at an efficiency of about 55% and gas consumption rate of about 19 MJ/h. The technical and economic feasibility of the biogas for power generation varies with technology and biogas quality while the use of biogas for vehicular operation requires some engine modifications. Generally, the efficiencies of the biogas utilization is 8%–54% for electricity generation, 4%–18% for transport, and 16%–30% for heat. Although liquid fuels generally have the advantage of being versatile and ease of transport, the direct use of biogas has higher efficiency [293]

2.23.15. Biomethane

Biomethane is a near-pure source of methane that can be produced by upgrading” biogas or through the gasification of solid biomass followed by methanation. Since bioethane is similar to regular natural gas stream, it can be transported and used as natural gas, but without adding to emissions as a clean fuel. Biomethane enables countries to reduce emissions in some hard-to-abate sectors, like heavy industry and freight transport and helps convert existing gas infrastructure more compatible with a low-emissions future, thus improving the cost-effectiveness and security of energy transitions globally. Therefore biomethane has a leading role in the energy transition as substitute for natural gas in a circular economy[28, 294].

2.23.16. Syngas and Producer Gas

Syngas, is made off a mixture of carbon monoxide and hydrogen, with potential use as a clean alternative to fossil fuel for power generation and feedstock for the production of liquid fuels such as synthetic diesel, dimethyl ether, and methanol. Syngas is a gasification product, from waste biomasses, known as “synthesis gas,” which is a mixture of H_2 , CO, and CO_2 that could be used as a potential intermediate in the conversion of biomass into fuel.. The production of diesel fuel from syngas relies on the Fischer-Tropsch process, which is a series of chemical reactions converting CO and H_2 into liquid hydrocarbon. Syngas can directly be used to power hydrogen fuel cells in a process where hydrogen is captured from the gas, and refined for use in fuel cells.

Producer gas is a mixture of carbon monoxide, hydrogen, carbon dioxide and nitrogen. Producer gas has a low heating value 5800 KJ/m^3 mainly because of nitrogen and carbon dioxide which dilute the gas. Therefore producer gas is also a gasification product but with significant amount of non-combustible gases mainly nitrogen and carbon dioxide, Other common terms used for producer gas are wood gas in the USA or raw gas. In the UK, producer gas, is often known as suction gas or a gas made from coke or other carbonaceous material. Producer gas is produced by passing air over the red-hot fuel leading to production of carbon monoxide in an exothermic reaction ; $2C + O_2 \rightarrow 2CO$. which leaves nitrogen in the air remains unchanged. The gas produced can be used to power gas turbines which can use low grade fuels[290].

2.23.17. Hydrogen

Hydrogen is the lightest element which at standard conditions, is a diatomic molecules which is sometimes called dihydrogen or molecular hydrogen or simply hydrogen. Hydrogen fuel is clean used in fuel cell with water as the waste product. Various feedstock can be used for hydrogen production e.g. natural gas, nuclear power, biomass, and renewable sources like solar and wind. Making hydrogen an attractive fuel for transport and power applications. Hydrogen can be widely used as an energy carrier for storage, movement, and delivery of energy produced from other sources. Hydrogen can be produced through several methods. Like natural gas reforming (a thermal process), and electrolysis and solar-driven and biological processes.

2.23.16.1 Thermal Processes

The thermal processes involve steam reforming, which is a high-temperature process in which steam reacts with a hydrocarbon fuel to produce hydrogen. Several hydrocarbon can be reformed to produce hydrogen, e.g. natural gas, diesel, renewable liquid fuels, gasified coal, as well as biomass. Close to 95% of all hydrogen is made through steam reforming of natural gas.

2.23.2. Electrolytic Processes

In the electrolytic process, water is separated into oxygen and hydrogen by electrolysis. In an electrolyzer, which operates like a reverse fuel cell which instead of using the energy of a hydrogen molecule, as in a fuel cell does, creates hydrogen from water molecules instead.

2.23.3. Solar-Driven Processes

In solar-driven processes hydrogen production, light is the agent for hydrogen production in processes like photobiological, photoelectrochemical, and solar thermochemical processes. In photobiological processes, the natural photosynthetic activity of bacteria and green algae is used. In the photoelectrochemical processes the specialized semiconductors are used to separate water into hydrogen and oxygen, while in solar thermochemical hydrogen production concentrated solar power is used to drive water splitting reactions along with other species such as metal oxides.

2.23.4. Biological Processes

These processes use microbes like bacteria and microalgae to produce hydrogen through biological reactions. Through microbial biomass conversion, the microbes disintegrate organic matter like biomass or wastewater for generation of hydrogen. In the photobiological processes the microbes apply sunlight as the energy source for hydrogen production.

2.23.18. Sugarcane bagasse

Bagasse is a the dry pulpy fibrous material that is left after crushing and extracting juice from sugar cane stalks with wide range of applications including biofuel production, combustion to produce heat, and electricity, and manufacture of pulp, paper and building materials.. Bagasse is a by-product of the cane sugar industry produced during the cane milling and is composed of the fibrous residue of juice extraction consisting of crushed stalks and leaves. Bagasse is abundant and readily available, making it an attractive feedstock for various applications. Global bagasse production is over 700 million tons per year, with Brazil and India being the largest producers. Bagasse is an attractive and abundant energy resource since sugarcane is a fast-growing crop, grown in over 110 countries globally while industry is constantly expanding leading to consistent supply of sugarcane bagasse. As a waste material produced during the production of sugar and ethanol, bagasse is readily available at a low cost, making it a desirable feedstock for many applications[295].

Physically, bagasse is a fibrous material which is light brown in colour and with a rough surface containing a high moisture content, of between 45% to 70%, depending on the milling condition, drying method and storage conditions. Bagasse is composed mainly of lignocellulosic compounds, like cellulose, hemicellulose, and lignin accounting for 40–50%, 20–30%, and 20–25% of the dry weight, respectively. Minor components of bagasse include ash, extractives, and proteins. Chemically, bagasse varies based on factors like age and variety of sugarcane, harvesting season, and processing methods[295].

The structure of sugarcane bagasse is complex and hierarchical, in nature consisting of various levels of organization, that include macroscopic, microscopic, and molecular levels. Sugarcane bagasse is composed of bundles of fibres at macroscopic level held together by a matrix of parenchyma cells, while at microscopic level, the fibres are composed of

microfibrils of cellulose embedded in a matrix of hemicellulose and lignin. Microfibrils have a diameter of about 3–4 nm and a length of several micrometres while at molecular level, cellulose is a linear polymer of glucose units, hemicellulose is a branched polymer of various sugar units, while lignin is a complex polymer of phenylpropane units. Cellulose accounts for 40–50% of the dry weight of sugarcane bagasse making it the main component. Cellulose is a linear polymer of glucose providing structural support to the plant cell walls while Hemicellulose is the second most abundant component, that accounts for 20–30% of the dry weight. Hemicellulose is a branched polymer of various sugar units providing flexibility and elasticity to the plant cell walls while Lignin is the third most abundant component, that accounts for 20–25% of the dry weight of sugarcane bagasse. Lignin is a complex polymer of phenylpropane units that provides rigidity and hydrophobicity to the plant cell walls. Ash, extractives, and proteins are minor components that account for less than 5% of the dry weight [295].

Other than a source of renewable energy, bagasse is an excellent source of cellulose from the fibers for various applications. However, the structure of sugarcane bagasse is different from other cellulosic fibers having a rind part, that is quite strong, yet the inner pith part contains weaker, smaller fibers making it hard to use in its raw state. Extraction of fibers or pure cellulose, nanocrystals or nanofibers require different techniques [295, 296]. Other fields of application for sugar cane bagasse includes both fully and partially biodegradable materials that match the currently ongoing trend of making a substitute for synthetic materials which makes sugarcane bagasse an excellent raw material for making environmentally friendly product [290]. Therefore bagasse has multiple competing applications as a resource besides energy source.

2.23.19. Magnetic energy

The word magnetohydrodynamic comes from two words, magneto- meaning magnetic field, and hydro- meaning liquid, and –dynamic meaning movement. The field was initiated by Hannes Alfvén who received the Nobel Prize in physics in 1970. Magnetohydrodynamics, abbreviated MHD, was originally intended to treat a plasma as a conducting fluid with the governing equations being adapted from fluid mechanics with appropriate modifications to account for electrical forces. Current was defined as a function of the applied electric field so

as to obtain a complete set of equations by using a linear Ohm's law, as used to describe conducting media. The net charge density for plasma was assumed to be identically zero since, plasmas are electrically neutral. Additionally, fluid motions tend to be slow compared to the characteristic time scales of a plasma hence displacement current was assumed to be small when compared to the conduction current. These stated assumptions, as well as appropriate equation of state, are sufficient to obtain a closed system of equations [297]. This provides a theoretical basis for precise definition of quantities, like fluid velocity and the plasma pressure. Therefore magnetohydrodynamic (MHD) (magnetofluid dynamics or hydromagnetics) is the study of the dynamics of electrically conducting fluids like plasmas, liquid metals, and salt water or electrolytes [297].

The concept behind MHD is that magnetic fields induce currents in a moving conductive fluid, that creates forces on the fluid and changes the magnetic field itself. MHD is defined by a set of equations combining the Navier–Stokes equations of fluid dynamics and Maxwell's equations of electromagnetism. The differential equations are resolved simultaneously either analytically or numerically[298]. The MHD operation is demonstrated in figure 2.9

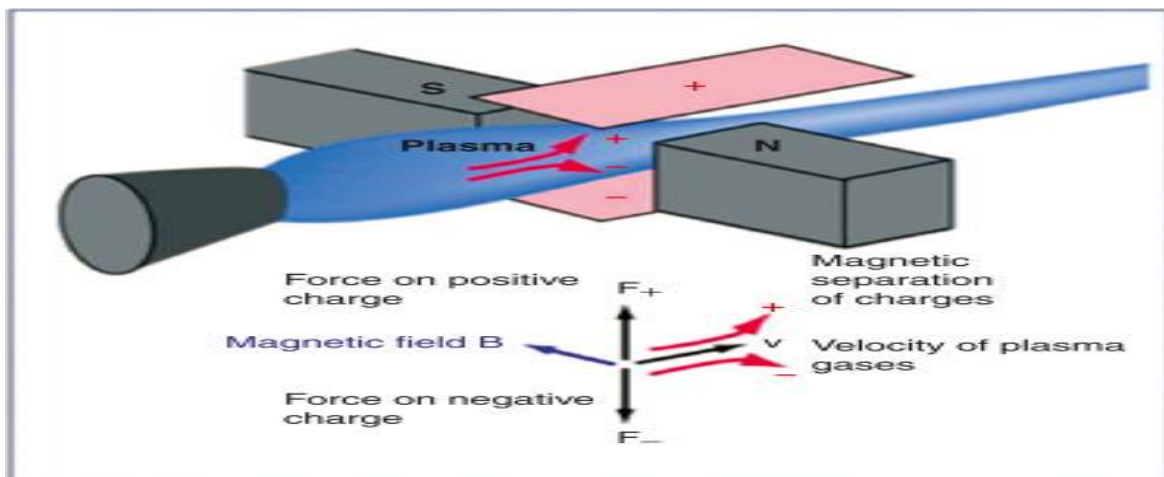


Figure 2.9 . Induced Current in a Moving Conductive Fluid in the Presence of a Magnetic Field

Figure 2.9 demonstrates the influences of the conductive fluid flow. Current flows down the screw and into the magnetic field, traveling at a 90° angle through the magnet and out the

wire. The magnetic field and current produce a force that is orthogonal to both forces, causing the magnet to spin while it is magnetically attached to the screw [298].

2.24. Power Plants for Electricity Generation

Electricity can be produced from different energy sources using power plants which vary based on the energy resource and applications.

2.24.1. Coal Power Plants

Coal-power plants account for over 10 billion tons of carbon dioxide annually which is about one fifth of global greenhouse gas emissions, making them single largest cause of climate change. China accounts for more than half of all the coal-fired electricity, while the number of coal power plants began to reduce in Europe and America in 2020. Due to failure to price the health and environmental cost of coal, coal power generation is seen as profitable in many countries[39].

2.24.2. Diesel power plants

Diesel power plants are power plants that use diesel cycle engines as prime movers powered mainly by heavy fuel oil or industrial diesel oil and with potential for conversion to gas engines or dual fuel engines. Therefore diesel power don't have to use diesel fuel, instead any fuel through appropriate modifications on the diesel engines can be used to power the engines for power generation. Both fossil fuels and renewable sources like biodiesel can be used to power diesel engines. The main challenges facing diesel power plants is high cost of power since consumers must pay for both the fuel and electricity produced. Fossil fuels are also affected by challenges of prices fluctuations of diesel and heavy fuel oil and high energy related greenhouse gas emissions have created demand for natural gas as an alternative fuel for power generation by diesel power stations and global supply chain challenges[280]. Diesel engines have wide applications in power generation for both grid and off grid applications. Diesel power plants vary in size and applications which include use as emergency plants, standby plants for main power stations, nursery plants, mobile power plants, and peak power plants. The strength and wide application of diesel power plants lies in their high load factors, high part load efficiency, ability to quickly start and stop and high fuel flexibility [280]

2.24.3. Gas turbine power plants

Gas turbines provide the most efficient way to generate electricity at large scale from gaseous fuels like biogas and natural gas. Gas turbines use hot flue gases as working fluids and with the main elements being the compressor, the combustor, the turbine, and auxiliary equipment. Gas turbines are characterized by high consumption of energy in compressing, low thermal efficiency for the open cycle gas turbines and environmental emissions from the consumption of fossil fuels. Open cycle gas turbines also emit exhaust at high temperatures with significant quantities of recoverable thermal energy while the thermal efficiency of an open cycle gas turbine is low, between 20 and 30% compared to 38 to 40% for a modern steam plant, which implies wasteful use of fuel power [299].

2.24.4. Nuclear power plants

Nuclear power plants use of nuclear reactions to produce electricity through mainly nuclear fission. Vast majority of electricity from nuclear power is produced by nuclear fission of uranium and plutonium in nuclear power plants. Nuclear decay processes are applied in a niche applications like radioisotope thermoelectric generators in space probes like Voyager 2[286]. Power generation from fusion power remains the focus of international research. Most nuclear power plants make use of thermal reactors utilizing enriched uranium in a once-through fuel cycle where fuel is removed when the percentage of neutron absorbing atoms is so large to the extent that a chain reaction can no longer be sustained, normally within three years. The fuel is then cooled for several years in on-site spent fuel pools for later transfer to long-term storage. Fast reactors on the other hand can reduce the duration significantly. Spent fuel which is mostly fissionable material, can be reprocessed by extracting fissile and fertile elements for fabrication in new fuel, in a more expensive process than producing new fuel from mined uranium. Reactors breed some plutonium-239, which is found in the spent fuel, is the preferred material for nuclear weapons, making fuel reprocessing as a means of weapon proliferation risk[286].

Nuclear technology is used to exploit the energy released by the splitting atoms of for heat and power generation. The technology was first used in the 1940s, and during the Second World War research initially in research focused on the production of bombs. The focus

shifted in 1950s to peaceful use of nuclear fission, for controlled use in power generation [300].

There are more than 18,000 reactors globally dedicated to civil use operating in 32 countries worldwide. The beneficiaries are more due to increased use of regional transmission grids, e.g. Italy and Denmark, gets about 10% of their electricity from imported nuclear power[300]. The applications of nuclear technology are many and extend beyond low carbon energy to include medical diagnosis and treatment, space exploration and military applications [300].

The first nuclear power plant was built in the 1950s while the global installed nuclear capacity increased to 100 GW in the late 1970s, and expanded to 300 GW by 1990. Nuclear accidents like the 1979 Three Mile Island accident in the United States and the 1986 Chernobyl disaster in the Soviet Union lead to higher regulation and public opposition to nuclear plants. Other limiting factors, to the development of nuclear power are high cost of construction, leading to the global installed capacity growth to 390 GW by 2022 with the nuclear power plants supplying 2,586 terawatt hours (TWh) of electricity in 2019, which was close to 10% of global electricity generation, and second-largest low-carbon power source after hydroelectricity. As of August 2023, the world had having overall capacity of 369 GW, with 57 under construction and 102 planned, with a combined capacity of 59 GW and 96 GW, respectively. The average global capacity factor for nuclear power plants is about 89% [286].

Nuclear power generation does not emit greenhouse gases and have one of the least less life-cycle carbon emissions indeed lower than some renewables. However, radiological hazards related to nuclear power generation and utilisation are the primary motivations of the anti-nuclear movement globally contending that nuclear power poses significant threats to people and the environment, with accidents like the Fukushima nuclear disaster in Japan in 2011, and and costly and slow deployment compared to alternative sustainable energy source[286].

2.24.5. Hydropower plants

Hydropower has a high potential for carbon emissions reductions in the global electricity system due to low greenhouse gas emissions (GHG), and a large potential for further capacity increase with low generation cost, compared to both other renewables and to thermal power plants. In total, generation by hydropower contributed nearly 17% of the worldwide electricity

supply in 2016, implying that > 1 billion people covered their electricity demand from hydropower. Hydropower is the third largest source of electricity generation, behind coal (39%) and natural gas (22%) but far ahead of nuclear (10%) [301].

Hydropower is the largest source of renewable energy in the electricity sector with a share of 68% of the renewables, more than twice all other renewables combined (32%). The technical potential for increased hydropower generation is large enough to meet substantial further deployment both in the medium (2030) and long term (2050). A realistic scenario is to double the annual generation (4102 TWh in 2016) to over 8000 TWh by 2050.

2.24.6. Biomass power plants

Biomass power plants generate electricity from the chemical energy in organic matter in the forms like wood waste, agricultural residue, animal waste, and energy crops. A biomass power plants generate electricity from the steam produced by combustion of plant or animal matter in a combustion chamber[302]. Biomass power plants burn fuel to produce steam which turns steam turbines to generate electricity just like in coal or gas-fuelled power plants with the main difference being the fuel used. Other than combustion of biomass to produce electricity, other methods like biomass gasification where biomass is heated in with less oxygen to produce hydrogen, although most biomass power plants use combustion to create energy, which creates the task of ensuring the combustion is as clean as possible[303].

2.24.7. Wind power plants

Wind power conversion from wind energy resource is influenced by the size of the turbine and the length rotor blades with output being proportional to the dimensions of the rotor and to the cube of the wind speed. Therefore, theoretically as wind speed doubles, the wind power potential increases by a factor of eight. Wind power generation has rapidly grown aided by research and development (R&D), supportive policies and reducing costs leading to growth in global installed wind generation capacity for both onshore and offshore by a factor of 98 in the past two decades increasing from 7.5 GW in 1997 to some 733 GW by 2018. The capacity of onshore wind increased from 178 GW in 2010 to 699 GW in 2020, while offshore wind generation grew from 3.1 GW in 2010 to 34.4 GW in 2020. Between 2009 and 2019, the production of wind power grew by a factor of 5.2 between 2009 and 2019 to reach 1412 TWh

while both onshore and offshore wind still have huge global potential for greater deployment and improvement

2.24.8. Solar Power plants

Whereas solar PV has experienced significant growth due to falling prices, solar CSP growth remained curtailed due to technical difficulties and high prices. And accounted for less than 2% global installed capacity of solar electricity plants [278]. CSP power plants consist of two parts namely one that collects solar energy and converts it to heat, and the one that converts the heat energy to electricity [277].

2.24.9. Ocean thermal power plants

The operation of OTEC plant requires seawater intake pipes to draw warm water from about 20m depth and cold water from 1000m. The water is mixed as it moves through the heat exchange and discharged at about 60m or deeper based on environmental impact analysis[304].

2.24.10. Wave power plants

Wave energy is exploited by diverting and focusing waves into a narrow channel to increase the size and capacity to rotate turbines for power generation. Common options are the catch basin, alternatively the reservoir can be used where the water flows to a turbine at a lower elevation, just like the way a hydropower dam operates[305].

2.24.11. Tidal power plants

Generation can be done using tidal barrages which use turbines integrated directly into the barrage wall. Water flows in and out of an estuary which can be natural or man-made basin and in the process drives the turbines, but with much reduced pressure head compared to hydro turbines in hydropower generation. Tidal barrages are most suited for placement across rivers or tidal basins having high tidal ranges, without the need for regular vessel navigation, and in areas without sensitive coastal ecosystems that would be disrupted by changes in water level and reduced access through the tidal barrage[289, 292].

2.24.12. Magnetohydrodynamic Power

In an MHD generator the hot gas is accelerated by a nozzle before injection into a channel. Having a powerful magnetic field. An electric field developed that acts in a direction perpendicular to both the gas flow and the magnetic field in accordance with Faraday's law of induction, with the walls of the channel which are parallel to the magnetic field serving as electrodes and to enable the generator to supply electric current to an external circuit [306].

The power generation by the MHD generator per cubic meter of its channel volume is proportional to the product of the conductivity of the gas, the square of the gas velocity, and the square of the magnetic field strength. The generators in MHD systems operate competitively and with reasonable physical dimensions, if the electrical conductivity of the plasma is in a temperature range above about 1,800 K (about 1,500 °C, or 2,800 °F). The value of electrical conductivity be 10 to 50 siemens per meter can be obtained if an additive, generally about 1 percent by mass, is injected into the hot gas in form of readily ionizable alkali material, like cesium, potassium carbonate, or sodium, referred to as the "seed." Cesium has ionizing potential (3.894 electron volts), and potassium (4.341 electron volts) Economic operation requires that the seed material should be recovered as much as possible , [297, 298, 303, 306].

2.24.13. Fuel cell power plants

Fuel cells are electrochemical systems used to continuously convert part of the free energy change in a chemical reaction to electrical energy. They operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2 , O_2), hydrazine (N_2H_4 , O_2), carbon/coal (C, O_2) methane (CH_4 , O_2). Therefore, a fuel cell is a device akin a battery that continuously recharges as it generates electric power using low-temperature electrochemical reaction oxygen and hydrogen. Unlike storage batteries whose main objective is to store energy, fuel cell fuel cells continuously generate if there is continuous supply of fuel and oxygen. Fuel cells employ an external or internal fuel-reforming process using any hydrogen-rich fuel can in different types of fuel cells. The main advantage of fuel cell systems like hydrogen fuel cells is that they are compact, light and have limited moving parts to attend to hence low maintenance and can realize 99.9999% reliability[307].

A fuel cell is a device akin a battery that continuously recharges as it generates electric power using low-temperature electrochemical reaction oxygen and hydrogen. Unlike storage batteries whose main objective is to store energy, fuel cell fuel cells continuously generate if there is continuous supply of fuel and oxygen. Fuel cells employ an external or internal fuel-reforming process using any hydrogen-rich fuel can in different types of fuel cells. Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO₂ emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cells reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85% .[308].

In a typical hydrogen–oxygen cell or hydrox cell, two porous or permeable electrodes made up of either carbon or nickel are immersed in an electrolyte of KOH solution. In this system, the electrochemical reaction takes place at the porous electrode where the gas, electrolyte and electrode are in contact is slow, hence the use of a finely divided platinum or platinum material is embedded in the electrodes. The concentration of potassium hydroxide (KOH) solution is kept between 30–40 per cent. It has a higher thermal conductivity and less corrosive compared to acids, making it popular [309].

2.24.14. Bagasse Cogeneration power plants

Bagasse like other biomass energy resources can be extracted by direct combustion or conversion into gaseous fuels like biogas and syngas and then combustion of the intermediate energy carriers to release energy. Anaerobic digestion of biomass involves bio-digestion of biomass with high moisture content in oxygen deficient to produce biogas. Gasification on the other hand is ideal for conversion of particularly for low-moisture biomass into syngas in as environment with limited amount of air at high temperatures [463].

Biomass energy resources can be extracted by direct combustion or conversion into gaseous fuels like biogas and syngas and direct combustion of the intermediate energy carriers to release energy, anerobic digestion of biomass through bio-digestion of biomass with high

moisture content in oxygen deficient and gasification by conversion of generally low-moisture biomass into syngas in limited amount of air at high temperatures[310].

A traditional sugar factory generally produces 10-20 kWh electrical energy/tc and consume 480-550 kg steam/tc, but modern sugar factories employing more efficient conversion systems generate 115-120 kWh/tc. Application of steam saving measures in the sugar factory releases steam from process and milling application to production of extra power. From various studies on bagasse cogeneration, it was established that reducing steam consumption from 500 by 30% to 350 kg/tc increases power generation by 24% while partial use of cane trash can increase excess power generation by or two folds[57, 81, 311].

2.24.15. International Power Sourcing

A sustainable energy mix incorporates onsite power plants, regional grids, and diversified conventional grid components, and the operation of such diversified resources can be made efficiently feasible using interconnectors and smart grids to provide the necessary infrastructure and capability [80, 312].

2.25. Energy generation and transmission enabling Technologies and concepts

The energy transition requires several technologies and infrastructure enable efficient and safe delivery of electricity from power plants to electricity consumers.

2.25.1. The smart energy concept

The concept of smart energy systems has emerged to accelerate the development of smart energy systems and achieve the carbon neutrality goal. [313]. Smart energy primarily applied to electric grid systems that incorporated the internet of things (IoT) and analytics, but currently has expanded, and today intelligent systems are applied all major industrial and corporate sectors. Sectors like transportation, power plants, OEMs, telecommunications, and many others apply data-driven and analytical solutions for intelligent energy management. Smart energy involves intelligent optimization of energy costs and efficiency by applying innovative technology to build and operate energy systems which is accomplished by integrating artificial intelligence, machine learning, and data analytics technologies into systems and processes using IoT sensors. They assist in data collection collecting data, monitoring, understand load, waste patterns, load, and other KPIs to optimize energy generation and consumption.,

2.25.2. Smart grid and microgrids

The energy transition towards sustainable energy systems requires advanced technologies like smart grids, energy management systems and renewable energy generation and storage solutions. To manage operation of such complex systems requires the integration and coordinating several power system components like advanced sensors and smart meters as main data sources in the era of big data, wireless communication, and application of the internet of Things (IoT) [314, 315]. Such data acquired should be stored, processed, and analysed to generate the necessary output for efficient deployment of energy resources and operation of power plants to match the prevailing demand and supply while integrating renewable energy and clean sources of energy. Very important in a modern power system is energy fuel efficiency, reduction of emissions and waste minimization[2, 3]. The benefits from such a modern grid include better asset management, enhanced operations planning, better monitoring and control, reduced cases of voltage instability, accurate prediction, and fault detection in a power system. Such advanced system also faces several challenges in implementation related to aspects like data uncertainty, data security, data quality, and data complexity[314, 315].

2.25.3. Decentralised generation

Decentralization of generation has generated global interest in the development of reliable and sustainable electric power systems as a strategy to use more local renewable and alternative sources of energy. In addition to reducing stress and loss in transmission , it reduces transmission and distribution losses [316, 317]. Decentralized generation uses different local energy sources to meet the demand of local electricity demand [316]. The integration and interconnection of distributed energy sources to the grid is challenging because traditional power systems are not usually designed to incorporate energy storage at distribution level[316, 317]. Another challenge with decentralized generation is that different sources have different characteristics hence a challenge on stability of a power system upon integration for example fuel cells and micro turbines large scale wind turbines and solar panels present different characteristics and hence impacts on the grid. Therefore there is need for clear definition of standards and procedures for integration of different distributed energy sources in distributed systems[316]. . Distributed generation helps to address twin challenges of generation

fluctuations and huge land requirements associated with wind and solar energy resources [58, 81, 226, 317].

2.25.4. Energy storage

Energy storage involves storing energy by means of equipment or media for release when needed. Energy storage is useful in balancing the demand and supply of electric power. The grid-level large-scale electrical energy storage (GLEES) converts energy from a grid-scale power network into a storable form for later conversion to electricity [318]. Many battery chemistries are either available or under investigation for grid-scale storage applications. They include lithium-ion, lead-acid, redox flow, and molten salt (including sodium-based chemistries). The use of utility-scale battery storage makes power systems more responsive to fluctuations in demand and supply and more flexible. Batteries support greater integration of variable renewable sources of energy to the grid, by storing energy from variable sources like solar and wind for later use. There is growing need for more flexible power systems to ensure more variable renewable sources are integrated efficiently and reliably[319, 320].

The battery storage systems have emerged as a potential solution to improve power system flexibility because of their ability to quickly absorb, hold and then reinject electricity. Utility-scale battery storage systems' capacity ranges from a few megawatt-hours (MWh) to hundreds of MWh. Recent years have seen most of the market growth dominated by in Li-ion batteries[321, 322]. The global increase in use of small-scale and distributed generation, and use of variable renewable have led to high demand for electrical energy storage systems (ESS), which applies different storage device. They include electrochemical storages, super capacitors, gravity batteries etc. The challenge is that we have no universally accepted economic indicator which for use in comparing compare different energy storage systems unlike in power plant planning where "Levelized Cost of Electricity (LCOE)" has been accepted[323]. Combining storage and renewable in a power system improves flexibility, which promotes adoption of renewable energy by ensuring security of the power grid. The future energy systems dominated by renewable energy will require largescale and wide application of energy storage technologies [324].

About 7200 gigawatts (GW) of electricity capacity must be built globally to keep pace with growing electricity demand and to replace retiring power plants by 2014. Future power

systems are expected to have large proportions of intermittent power like wind, solar and tidal generation and or inflexible. nuclear, coal, *etc.* There is need to scale up storage scale-up energy storage to match the electricity supply with hourly, daily, and seasonal electricity demand profiles. According to the International Energy Agency, about 310 GW grid grid-connected electricity storage capacity will be needed by the US, Europe, China and India[325].

2.25.5. Cogeneration and trigeneration

Biomass based cogeneration is about 3.3 times more energy-efficient than coal-based independent production. Cogeneration from the same fuel was in all cases 0.3 times more energy-efficient than independent production. In general heat and power production from biomass is 2.3 times more energy-efficient than that from coal in a similar process. The energy sustainability index shows a similar trend, e.g., the sustainability index of a biomass CHP plant is 15 times higher than that of a coal CHP plant. The fuel, its transport, and the oxygen in air used for burning account for over 80% of the energy in biomass CHP, whereas in a coal-based process the share is over 90%. The share of capital is quite small in terms of total energy[59, 81, 326].

The co-generation of energy products is accounted for in the LCA studies preferably with system expansion in accounting for co-production or multifunctionality as long as subdivision of the multifunctional processes is not possible. This method or approach may be practical in relation to life cycle assessment (LCA) of the entire electricity systems. This is because heat generation itself is an integral part of the system. Thus, the system expansion and substitution with alternative means thermal generation involves an entirely different energy supply system. System expansion is appropriate for countries with marginal shares of combined heat and power (CHP), while for the case of a country like Denmark, the allocation of emissions may be applied for power system[327, 328].

Cogeneration process produces mainly two types of products i.e. electricity and heat, while trigeneration also involves cooling. For cogeneration and trigeneration, different methods are applied to distribute the environmental impacts between the products based on energy, exergy, the value of emissions, fuel chargeable to power, shared emissions, and other methods. The effective integration of renewable and traditional energy sources and the proper operation of

thermal systems can improve system flexibility and sustainability [329]. The efficiency of cogeneration varies with the type of primary energy used and cogeneration technology applied [296, 329].

Cogeneration involves various concepts and technologies through which heat, and electric are power jointly produced by a system. There is a potential to generate more electricity than needed for internal use with excess electricity being exported to the grid to earn an extra revenue stream[81]. with the option of the excess energy being fed into the public grid could help in saving this energy. Cogeneration results to high levels of efficiency of about 85%, because of using waste energy as a co-product of electricity generation[101, 330].

Cogeneration systems for diesel power plants make use of different devices, but the basic elements are the electric generator, Rankine cycle steam turbine, the engine, heat recovery equipment like exhaust gas boilers, superheaters, and system control devices. The steam turbines are the prime movers with various options whose performance and application may also vary e.g., condensing turbines, back pressure turbines and extraction turbines[81, 331]. Based on the lower heating value of fuel used, cogeneration systems, have efficiency greater than 80% compared to an average of 30–35% in conventional thermal systems generation systems and up to 55% for the case of combined cycle power plant systems like in gas turbine combined cycle gas turbine[101, 299, 330, 332, 333]. The main benefit of the increased energy efficiency is low energy expenditure and reduction in generation related greenhouse gas [334].

2.25.6. Electrification of transport and Coupling of Transport and Power Sectors

Passenger transportation accounts for 50 to 60% of energy consumed by the transport sector with private cars being the dominant mode of passenger transport [335]. The freight transport accounts for 40 to 50% of the transport sector's energy consumption. For most economies globally, road transport accounts for 80% of domestic energy consumption. Rail and maritime shipping are more energy-efficient modes with greater marginal energy consumption levels. [335]. The transport sector activities account for between 25 and 30% of all greenhouse gas emissions globally [335].

Road and rail transport constitute the principle mode of transport for people and cargo most of which are driven by fossil fuel powered internal combustion engines [336]. Electrification

of transport can reduce greenhouse gas emissions, minimise dependency on fossil fuel sources, enhance the deployment of renewable energy sources, reduce the dependency on fossil fuel and mitigate the release of ozone depleting substances. The concept of Vehicle-to-Grid creates an import opportunity for vehicle owners to supply power to the grid and generate some revenue as a key pathway for the energy transition [337].

The electric vehicles market is growing rapidly, e.g. Germany realised a 263%, growth, France, 202% and the UK 140% rise in sales of plug-in electric passenger cars in the year 2020. The US and China which have largest EV market realised smaller growth of 4% for U.S. and 15% for China. China is the world leader in sale of plug-in electric vehicles (PEVs), but Europe dominate plug-in car sales in 2020 with Norway, Iceland, and Sweden leading at 74.8%, 28 45%, and 32.3% shares, respectively [338, 339]. The global stock of electric cars hit the 10 million mark, or 43% increase over the previous year in the year 2020. Electric vehicles accounted for two thirds of new electric car registrations in 2020 with China having the largest fleet of four and a half million electric cars in 2020. However, Europe had the largest annual increase, with electric vehicles stock hitting 3.2 million [340]. This is a significant growth compared to data for 2012, which showed that the global EV stock was 180,000, or 0.02 % of total passenger cars. The projection is that the share will reach over 2 % by 2023 [339]. This growth trend in the electric vehicle market demonstrates the significant potential of this sector in the global energy transition [35].

There are many energy in the transport sector, but use of diesel and petrol still dominates the transport sector [341]. Other options include natural gas, biogas and bio methane, fuel cells with studies showing that use of biogas and fuel cell hydrogen trucks can significantly reduce greenhouse gas emissions and therefore when it comes to economic viability, the use of natural gas and hybrid trucks seem to offer best substitutes to diesel and petrol [341]. Many transport sector low carbon transitions models are based on decarbonisation in terms of technological transformation, but we have opportunities for behavioural or demand side orientated measures[342]. Therefore the transport sector has an important role to play in economic development especially by facilitating choices among consumers like where to live, where to work, how and where to spend your leisure hours [341]. The transport sector also offers employment to millions of people globally. The combined passenger and freight transport accounts for about 20% of the global greenhouse gas emissions[342]. Passenger cars

account for emissions of around five gigatons of CO₂ per year which is like the entire CO₂ emissions of the US which currently is world's second, largest polluter. While household heating is responsible for about two and a half gigatons of CO₂ emissions per year, that is similar to the entire CO₂ emissions of India, which is the third largest polluter globally [2, 341].

The internal combustion engine which is the traditional prime mover for the transport sector has a conversion efficiency of about 12.7%. Pure electric vehicles on the other hand have a conversion efficiency of about 51.6%. Fuel cell vehicles (FCVs) have efficiency of 28.3% and hydrogen ICE (HICE) vehicles have 26.6% conversion efficiency [343]. With electrification, if vehicle charging is not intelligently managed, the effect will be increasing peak loading on the electricity infrastructure which will call for major infrastructure investment to avoid supply failure. The solution is to use smart grid technology to facilitate strategic charging when demand is low to utilise low-cost generation and extra system capacity, or charging when renewable electricity contributor to the power mix is high [98, 344].

2.25.7. Demand side and Behind the meter management

Matching demand and supply in real time ensures that the power grid is stable. In the traditional setup, generation must be increased in response to growing load demand. Demand side management (DSM) concept includes application of measures like energy efficiency and demand response (DR), by working from the consumer side. The U.S. Department of Energy defines demand side management as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized for some reason” [3]. The role of demand side management (DSM) programs is to motivate the electricity consumers to modify their consumption pattern by reducing consumption in a way that it is shifted from the peak. DSM is an indispensable component of microgrids for application in direct load control or real-time electricity pricing. As a result of the restructuring of power system and establishment of electricity market, the electricity prices fluctuate based on the time and location of consumption/generation [322, 326].

2.25.8. Carbon Capture and Sequestration

The CCS is a promising approach for reduction of GHG emissions by capturing carbon dioxide (CO₂) at the point of power generation and transporting to an injection site and sequestering for long-term storage in suitable formations. A CCS unit at thermal plants can efficiently capture about 85–95% of the CO₂ processed in a capture plant[345].

Emissions from fossil fuels have been increasing by 2.7% annually over the past decade and now are 60% above 1990 levels. By reducing emissions by at least 50%, we can limit the rise of the global average temperature to 2 °C by 2050. Carbon capture and sequestration (CCS) faces technical and economic barriers that must be overcome before large scale deployment since it is an unprofitable activity that requires large capital investment, yet some countries like UK, has no incentives or subsidies for CCS. Technically the CO₂ leakage is uncertain and in some countries it is not a viable option since geological storage capacity is limited or in some cases only available offshore, which increases the transportation and injection costs for countries like the UK, Norway, Singapore, Brazil, and India.

Recently, carbon capture and utilization (CCU) is used to turn waste CO₂ emissions into valuable products like chemicals and fuels, and contribute to climate change mitigation. The utilization of CO₂ is usually a profitable activity with the possibility of selling the products. When compared with conventional petrochemicals feedstocks, CO₂ is a ‘renewable’ resource on condition that it is continuously emitted by various industrial activities, it is low in cost and is non-toxic. The thermodynamic stability of CO₂ making conversion to various products an energy intensive activity. However, the potential of a secure supply of chemicals and fuels, along with the increasing fossil-fuel prices is a powerful driver for CCU.

2.25.9. Oil and Coal shift to Natural gas

Natural gas can simultaneously reduce the cost of generation per kilowatt-hour(kWh) and emissions when used in place of more polluting fossil fuels like oil and coal. In the case of oil or diesel to natural gas, the conversion process involved modification of the fuel injection system to cope with new fuel injection and ignition requirements, new control for fuel injection and reduced air to fuel ratio and lowering of the engines’ compression ratios through increase of the engine cylinder clearance volume. The conversion requires provision for natural gas storage facilities and supply system which were introduced in the proposed design

modification. The dual fuel mode proposes a diesel/natural gas ratio of 1:4, which reduced the diesel specific fuel consumption (sfc) from 3400kg/h to 640kg/h hence 81.2% reduction with natural gas consumption of 2,196.72 kg/h. Based on prevailing local heavy fuel price of ksh 46/litre (US\$0.46/litre) and natural gas cost of \$605/tonne and power plant load factor of 0.5, the total annual fuel savings would amount to ksh 453,407,867.60 (US\$ 4.5 million). These fuel savings will influence renegotiation of the power purchase agreement resulting into lower tariffs, higher load factor and power plant utilization which translates to more revenue and reduced unit cost of power with lower environmental impact as well as better return on investment. The main challenge of the conversion is lost generation related to the conversion, and the global delay towards the

2.25.10. Plastic Pyrolysis and Pyrolysis oil Production

There are four main avenues available for plastic solid waste treatment, namely re-extrusion as a primary treatment, mechanical treatment as secondary measures, chemical treatment as a tertiary measure and energy recovery as a quaternary measure. The pyrolysis oil made from plastics has properties that are close to clean fuel and therefore a substitute for fresh fossil fuel for power generation, transport, and other applications. This study showed that waste plastic pyrolysis offers an alternative avenue for plastic waste disposal and alternative source of fossil fuel to reduce total demand of virgin oil. Through plastic pyrolysis, plastic wastes are thermally converted to fuel by degrading long chain polymers into small complex molecules in the absence of oxygen making it a technically and economically feasible process for waste plastic recycling. The process is advantageous because presorting is not required, and the plastic waste can be directly fed without pretreatment prior to the process. Products of plastic pyrolysis a pyrolysis oil, hydrocarbon rich gas, with heating value of 25–45 MJ/kg which makes it ideal for process energy recovery. Hence the pyrolysis gas can be fed back to the process to extract the energy for the process heating purpose which substantially reduces the reliance on external heating sources.

2.25.11. Modular Power Plants

Modular or containerised power plants have emerged as a sustainable alternative to the conventional power plants especially for expensive power plants with long lead times like the nuclear and geothermal power plants. Modular power plants are based on proven technologies

that come as factory-manufactured and tested modules. The modules are manufactured and preassembled in the factory which enables faster project implementation, shorter site time and completion with higher quality and lower implementation risks. In nuclear power generation, Small modular reactors (SMRs) are modularised reactors with capacity of up to 300 MW(e) per unit, which is about one-third of the generating capacity of traditional nuclear power reactor [346].

Geothermal energy has a significant role to play in the global transition to renewable and low-carbon energy systems because of its ability to supply steady and flexible electricity particularly for baseload demand because of its cost competitiveness compared to fossil fuel energy options. However, geothermal faces a challenge of long project development times with conventional power plant taking an average of 5–10 years and with high risks associated with drilling of unproductive wells which discourage private investment and quick deployment. Although geothermal energy has a huge potential for power generation, it currently contributes less than 1% of global electricity generation capacity. The generation capacity grew from 8.7 GWe in 2005 to 15.61 GWe at the end of the year 2020, representing average annual growth of 4.01%.

Wellhead power plants can be used on temporary basis during the project development or permanently as grid connected or off grid generation facilities. With current technology, wellhead generators of up to 15 MW capacity can be installed on well pads of production wells for temporary or permanent electricity supply. Wellhead generators can facilitate optimum resource utilization especially for wells with unique conditions like too high or too low pressure and temperature compared to others in the same steam. They are generally inferior to central power plants due to lack of economies of scale hence higher unit cost of power. Successful adoption of wellhead powerplants for faster electrifications calls for state support and incentives in terms of subsidies, development of electricity grid, attractive feed in tariffs and tax incentives without which they won't compete favorably against the conventional central powerplants. Generally, wellhead powerplants can make geothermal electricity projects more feasible with reduced barriers in investment and early electricity and revenue generation for investors. However, investment on temporary basis makes reasonable economic sense if the time between drilling the first productive well and completion of a central plant is

more than one year. Incentives like high feed in tariffs and tax incentives may be necessary to make them competitive against the superior conventional powerplant [44, 346-348]

2.25.12. Waste to energy conversions

With growing population and increased urbanization, landfills, and various greenhouse emissions (primarily methane) are also growing at high rates globally. Turning waste into energy is a sustainable way of diverting waste like trash from landfills into something truly useful through waste-to-energy technologies having varying degrees of footprints and efficiency. Waste to energy sector is largely underutilized around the world, but it has an attractive future outlook at this time when global energy insecurity has reached a new distressing peak. Simply put, waste-to-energy refers to any process that converts trash or waste to usable energy. Waste-to-energy solutions may turn gaseous, liquid, and semi-solid waste into heat, fuel for transport, or electricity. It is non-recyclable waste that is preferably used by waste-to-energy technology.

There are different types of waste-to-energy technologies based on the process through which the waste is turned into energy. The types are thermal only, like incineration, thermo-chemical, mechanical & thermal, and biochemical. The thermal WtE plants are most common systems for handling MWT. Incineration remains the least favorable options because incineration these plants are costly to operate and produce higher emissions.

2.26. Chapter Summary and Discusion

2.27. Chapter Conclusions

The global energy system must shift from reliance on nonrenewable and fossil fuel sources to renewable and low carbon sources especially for electricity generation mainly from solar, wind, geothermal and other natural energy resources as well as low carbon nuclear power generation. Such a transition will lead to substantial increase in system efficiency and reduction of greenhouse gas emissions to achieve a 1.5 °C temperature rise target set by the Paris Agreement. Wider electrification of energy end-use applications like transport and heat as well as electrification of most industrial and domestic energy services will make electricity the backbone of the world's energy supply which is easier to control and manage.

Sustainable energy is best analyzed with five dimensions namely social, economic, environmental, institutional, or political, and technical, the sustainable transition strategies

typically consist of three major technological changes namely, energy savings on the demand side, generation efficiency at production level and fossil fuel substitution by various renewable energy sources and low carbon nuclear. For the transition to remain technically and economically feasible and beneficial, policy initiatives are necessary to steer the global electricity transition towards a sustainable energy and electricity system. Whereas renewable sources energy holds the key for sustainable energy transition, large-scale renewable energy adoption should include measures to improve efficiency of existing nonrenewable sources which still have an important cost reduction and stabilization role. A resilient grid with advanced energy storage for storage and absorption of variable renewables should also be part of the transition strategies.

The greatest sustainability challenge facing humanity today is the greenhouse gas emissions and the global climate change with fossil fuels led by coal, natural gas and oil contributing 61.3% of global electricity generation in the year 2020. Through sustainable energy, the dependence on fossil fuel sources is reduced while increasing the use of renewable sources of energy thus reducing greenhouse gases. Renewable energy technologies may be divided into three generations. The first generation commenced in the nineteenth century and relied on hydropower biomass and geothermal energy. The second generation started in the 1980s and consisted of consists of tidal, wind power, wave power, and solar energy. The third stage or generation is still under development today and is based on gasification, bio-refinery, and ocean thermal power. Electricity is the most dominant form of energy deriving its supply from both renewable and nonrenewable sources. The optimum operation of the grid electricity system is influenced by many dynamic variables which must be determined and controlled, managed, or accommodated to deliver reliable, affordable, and clean electricity. Sustainable grid electricity transformation needs competitive and cost-effective financing mechanisms to accelerate the transition, needs reliable energy supplies, and application of effective business and operation modelling tools that can deliver sustainable electricity which also needs new technology and data capability to analyze, and optimize results on real-time basis and in medium- and long-term planning.

Technology has a very important role to play in the transition to a low carbon electricity grid and economy. Technology options to facilitate the energy transition will include rapid digitalization of the energy sector which will enhance its flexibility and resilience to absorb

variable renewable sources of energy particularly wind and solar. Important technology include transition from the traditional grid based on centralized generation to smart grids which support decentralized generation and ability to absorb the fluctuating renewable energy sources like solar and wind and fluctuating demand like electric cars while guaranteeing a stable and reliable electricity supply. Decentralization and enhanced use of variable renewables will further be enhanced by use of micro grid technology. With use of micro grids, it is possible to balance generation from variable renewable power sources such as solar, wind, and hydro and conventional sources like gas-fueled combustion turbines, coal, and diesel power plants. Since greenhouse gas emissions come from sectors like extraction/refining, power generation and direct transport, agriculture, industry, and homes, electrification of all industries and homes with power coming from renewable sources of energy will greatly succeed in cutting down global emissions. The broad strategies adopted for sustainable transition include liberalisation and restructuring of electricity and other energy markets which is made attractive by ever growing energy demand globally. Key policies adopted should aim at making electricity markets work better. More research and development into efficient, environmentally friendly, and competitive technology is needed to facilitate innovation and diffusion of sustainable energy technologies. To successfully implement these policies calls for reduction unit cost of electricity and affordable cost of appropriate energy carriers and services, plus regulations to increase efficiency and reduce energy related environmental for greater public benefits.

The implementation of effective sustainable energy technologies to minimize carbon emissions will require the use of renewable and low carbon sources of energy and adoption of three main strategies namely conventional mitigation, negative emissions technologies which capture and sequester carbon emissions and finally technologies which alter the global atmospheric radiative energy budget to stabilize and reduce global average temperature. Besides low emissions, a sustainable electricity grid system should be stable and supply reliable, affordable, and socially acceptable electricity.

Although there is no consensus on quantitative factors and their magnitude there is agreement on the need for supportive policies, regulations, programmes, and international commitments. Other measures are the development and expansion of financial sector, and improvement on the performance and quality of energy sector institutions. This chapter concludes that both

renewable and non-renewable sources of energy have an important role to play in the short and long-term sustainable energy transition. Potential energy sources for a sustainable energy and electricity mix are solar, wind, hydro, hydrogen, bioresources, marine energy, nuclear, natural gas substitute of other fossil fuels and application of clean and efficient technologies for existing fossil fuel and non-renewable systems.

Appropriate strategies, technologies and concepts for the sustainable transition include electrification of industrial and domestic thermal applications, use of technologies like smart grids, energy storage, carbon capture and sequestration, cogeneration, and various other energy efficiency measures to limit consumption and wastage of energy resources. Waste to energy and particularly in form of electricity will minimize solid waste load and reduce environmental pollution like water and soil contamination. With the grid connecting different energy sources and infrastructure, decision support systems and optimization models will play a key role in realizing cost effective and environmentally friendly and reliable electricity generation and supply. Technology measures to control global warming can be classified into three broad categories of carbon capture and sequestration, emission mitigation strategies and technologies that alter the radiative properties of incoming and outgoing solar radiations.

2.28. Recommendations

This study lays the foundation for further research into technical and non-technical measures to ensure a sustainable transition to a low carbon electricity grid from different sources of energy, both renewable and nonrenewable and will form a firm foundation for effective policy formulation and implementation necessary to drive the energy transition globally.

Developing countries should avoid going down the path taken by most developed countries by limiting dependence on fossil fuels for their energy needs through greater use of renewable energy sources while relegating the use of fossil fuels for peripheral role of stabilising the electricity grids. Through decentralisation of power systems, countries achieve accelerated energy transition. This however does not imply that a country can leapfrog to 100 per cent renewable energy grids with many models proposing carbon neutrality by 2050. This study demonstrates the significance of renewables and low carbon nuclear for the energy transition but notes that fossil fuels can play a role of stabilisation being dispatchable sources.

CHAPTER 3:

REASEARCH METHODOLOGY

3. Overview

This chapter describes and lays the foundation for the planning and modelling used in this study, outlines the major dimensions, parameters and indicators of sustainable energy and electricity for use in comparing and priority ranking of energy sources and conversion systems for electricity generation. This thesis relies on the characterisation of technologies and power plants to identify optimum mix of sources to meet the ever-varying electricity demand and supply as projected in the load curve and real time situation that may not be predictable. The overall process involves characterising energy sources and power plants and conceptualising the power system status, in the long run, short-term and real time.

There is growing electricity demand globally because of economic growth, population growth, increased electrification of remote areas and processes previously using other sources of energy like transport. The greatest sustainability challenge facing humanity today is the greenhouse gas emissions and the global climate change with fossil fuels led by coal, natural gas and oil contributing 61.3% of global electricity generation in the year 2020.

Many previous studies and electricity plans are based on the least cost energy plan limited to technical aspects like dynamic power consumption and demand forecasting; techno-environmental for example carbon capacity expansion; techno-economic electricity expansion aspect and economic, techno-environmental electricity. Little effort is done to evaluate and plan current and future energy and electricity based on sustainability dimensions in selecting and prioritization of energy sources and power generation technologies. This study aimed at identifying, selecting, prioritizing, and ranking future energy and power technology based on sustainable dimensions of economic, technical, social, environmental, and institutional.

In this research, sustainability of energy and power generation is assessed by a five-dimensional approach to sustainability. These five comprehensive aspects are environmental, social, economic, technical, and institutional. This research applied multi-criteria decision making (MCDM) method considering several variables to make energy and technology investment decision for global and individual country specific grids. Energy options and

conversion technologies were evaluated based on the five dimensions of energy and several energy and technology sustainability indicators by applying a hybrid AHP–TOPSIS technique. This research provides a very important policy contribution to governments, energy agencies and investors project investors to solve the dilemma of technologies prioritization in energy and electricity planning.

3.18. Research Design

The research design is the overall strategy and analytical approach adopted to integrate, coherently and logically, the different components of the study, in a way that the research problem is thoroughly investigated. A research design constitutes the blueprint for data collection, measurement, and interpretation of data and information within the confines of a research problem which determines the type of research design chosen. The main function of a research design is to facilitate collection of evidence which enables effective, logical, and unambiguous address approach to a research problem [148]. This study applied mixed research design of qualitative and qualitative designs. The mixed method is characterized by a focus on research problems that require,

- i. an examination of real-life contextual understandings, multi-level perspectives, and cultural influences.
- ii. an intentional application of rigorous quantitative research assessing magnitude and frequency of constructs and rigorous qualitative research exploring the meaning and understanding of the constructs; and,
- iii. an objective of drawing on the strengths of quantitative and qualitative data gathering techniques to formulate a holistic interpretive framework for generating possible solutions or new understandings of the problem.

The mixed design encompasses more than simply combining qualitative and quantitative methods but, rather, reflects a new epistemological paradigm that occupies the conceptual space between positivism and interpretivism [148].

3.18.1.Quantitative Research Design

The study applied quantitative research design to generate quantitative data like power plant performance indicators whose results were presented through quantitative analysis like statistics, graphs, charts, and numbers [148]..

3.18.2.Qualitative Research Design

The study also applied qualitative research design to seek answers to how to manage the transition and why the world community should mitigate emissions The qualitative uses open-ended questions and approaches to helps the subjects express their views clearly. The aim of qualitative research aims to understand consumer' behavior and requirement [148].

3.18.3.Experimental Design

Experimental research design looks at a problem scientifically to establish a clear cause and effect of every event. Experimental research design also attempts to understand the impact of the independent variable on the dependable variable [148].

3.18.4.Correlational Design

The study also applied Correlation research design to establish the relationship between two related variables. Through correlation research design relationship between variables are established[148]..

3.18.5.Descriptive Design

The research also applied descriptive research design methods in which data was collected through observations, case studies, and surveys to derive results.

3.18.6.Diagnostic Design

In this research design, the reason behind scenarios and their solutions are investigated. In this approach, the research solved e problems in a structured form divided into three phases- the

issue's inception, diagnosis of the issue, and solution to energy and environment challenges [148].

3.18.7.Explanatory Design

In this research design, the researcher investigated concepts and ideas on various subjects in energy and power generation like the use of municipal solid waste and waste plastics in the energy transition through literature survey with theories being explored more theories. The objective was to explore undiscovered aspects, any ongoing research and results that are not widely known. An exploratory design is usually applied about a research problem having few or no earlier studies to refer to predict an outcome, with the focus being to gain an insight and familiarity for later investigation. Exploratory design is also done research problems is at a preliminary stage of investigation and are used to establish an understanding of how best to proceed in studying an issue or determine what methodology to effectively apply to gather information about the problem [148]. In this study, exploratory design was applied to investigate new technologies and their impacts.

3.18.8.Case Studies

A case study is defined as an in-depth investigation of a particular research problem rather application of a sweeping statistical survey or comprehensive comparative inquiry, often applied to narrow down a broad field of research into one or a few easily researchable examples. This research design is also ideal for testing a specific theory, assumptions and model in the real world. [148]. Case studies were applied to investigate specific power plants and conversion technology in real life by carrying out performance analysis and reviews. Various case studies are presented in this study on various cases that can transform the energy sector particularly related to power generation like waste to energy or electricity options and technologies from the industry.

3.18.9.Systematic Review

A systematic review is a specific methodology which identifies existing research about a well-defined topic of investigation, usually derived from a public policy or clinical, practice-based

problem. A systematic review research design involves selecting and critically evaluating the contributions of the identified subject by analyzing, and carefully synthesizing the data, and reporting the evidence in a manner that enable clear conclusions about the unknown. A systematic review is a self-contained research project that explores a clearly defined research problem by using existing studies, whose design differs from other review methods due to application of distinct and exacting principles to the evaluative process of analyzing existing literature. Published and unpublished studies concerning the problem being investigated are located and evaluated in the analysis [148]. This method was applied to technologies and energy sources that are still evolving like hydrogen, fuel cells and biomethane.

3.19. Data Collection: Methods and Sources

Data refers to a collection of facts, figures, objects, symbols, and events collected from different sources. Data is needed to make decisions or judgement about a problem being investigated, so with no data it would be difficult to make appropriate decisions, so data is collected from different audiences at various points in time. Data collection methods refers to techniques and procedures applied to gather information for use in research. The techniques range from simple self-reported surveys to more complex experiments and involve either quantitative or qualitative approaches to data gathering. In this study, data collection methods applied include surveys, interviews, observations, focus groups, experiments, and analysis of secondary data [148]..

3.19.1.Data Collection Methods

There are various methods and instruments for data collection as summarised in Figure 3-1.

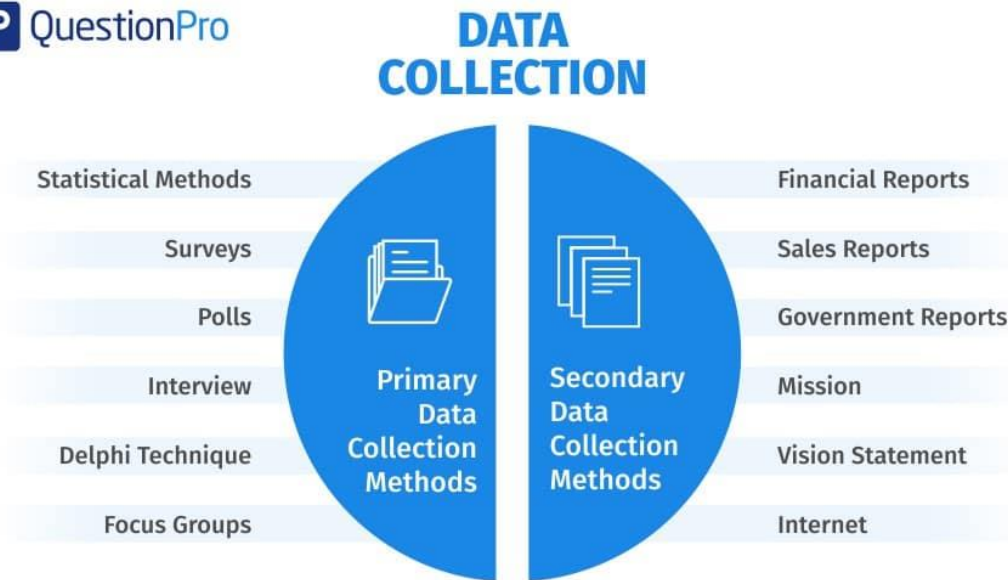


Figure 3-1: Summary of data collection methods and instruments.

Figure 3-1 shows the various instruments for research data collection. The methods include statistical methods, surveys, polls, interviews, Delphi technique and use of focus groups. The sources of data include financial reports, sales reports, generation reports, mission statements, the internet and vision statements.

3.19.2.Importance of Data Collection Methods

Data collection methods are important in the research process since they determine the quality and accuracy of the data collected. The importance of data collection methods is.

- i. Determines the accuracy and quality of collected data.
- ii. Data collection method facilitates collection of relevant, valid, and reliable data for research.
- iii. The collection methods help reduce bias and increase the representativeness of the sample.
- iv. Data collection methods are essential for accurate conclusions and decisions.
- v. It is through proper data collection method that the research achieves the set objectives by providing accurate data.

- vi. Good data collection methods support the validity and reliability of research findings [148].

3.19.3. Methodology Used

This research applied mixed approaches and data including case studies, performance analysis and review of operating energy systems, proposed energy system design, and design analysis, and modelling of future/proposed energy systems using modelling and simulation tools. [148].

3.19.3.1. Observation Methods

Observational methods involve examination of things and collection of data about them. It includes observation of individual energy and power systems in their point of operation [148].

3.19.3.2. Survey Methods

Survey methods are applied to collect data using written or multiple-choice answers about various subjects. It involves individuals interacting with these questions online and with little to no interaction between survey distributors and survey respondents. It can be applied use to collect quick internal or external feedback. [148].

3.19.3.3. Interview

Interview methods involved face-to-face discussions about the problem between the researcher and participants. The questions may be shared with participants before the interview sessions [148].

3.19.3.4. Lifecycle Assessment

The content of this section is published in publications [22, 23, 39, 186] on life cycle assessment of energy systems. It was observed that life cycle assessment (LCA) refers to the holistic approach applied in evaluation of the environmental impacts of energy sources and other products as well as systems. In the energy sector, life cycle analysis (LCA) helps in fostering development of energy technologies in a sustainable manner [349]. LCA remains a powerful tool used in evaluation of the environmental performance of energy sources, products, processes, and production systems. LCA studies on power generation can focus on the evaluation and calculation of single types or multiple types of power to identify environmental advantages of specific power types or provide the basis for policy and energy

conservation measures. Studies show that greenhouse gas emissions intensity of various technologies greatly varies between regions and sources [350].

There is a need for well-informed energy policy design information to attain the decarbonization targets and keep global warming below 2°C threshold set by the Paris agreement. Low-carbon electricity supply for all is needed to attain the 2°C-compatible energy system for maximum electrification of economies. Life cycle assessment facilitates the evaluation of a product over its life cycle, and across various environmental indicators. Technologies assessed include coal, natural gas, hydropower, nuclear power, concentrated solar power (CSP), photovoltaics, and wind power. Life cycle assessment is a tool used to evaluate the environmental impact of energy sources. One major limitation of the standard life cycle assessment methodology is that it ignores the impact of the impact of greenhouse gases. Life-cycle impacts decrease substantially when current fossil fuel technologies diminish in the energy mix, particularly coal. Natural gas use may play an important role during the transition while installation of new fossil options without CO₂ capture should be avoided to minimize emissions. The endogenous integration of life-cycle indicators into energy planning models adds value to both life cycle assessment and energy systems modelling in their support in energy decision as well as policymaking for sustainable energy transition. Different power generation technologies have variations with respect to environmental impact, operational cost, and other factors. Each technology produces different levels of greenhouse gas (GHG) emissions, through construction, operation and decommissioning with coal fired power plants releasing most emission per unit power generation.

Life Cycle Analysis (LCA) is comprehensive form of analysis which applies the principles of Life Cycle Assessment, Life Cycle Cost Analysis, and v other methods for economic, social, and environmental, aspects of energy systems across their life cycle, from raw materials extraction or mining to applications as an energy carrier to perform work. The results of a lifecycle assessment are used to evaluate energy options [351]. It is therefore a holistic approach applied in evaluating the environmental impacts of products and systems through their entire life. Life cycle analysis helps to foster the development of energy technologies in a sustainable manner [349]. Life cycle assessment (LCA) is a decision support tool which assesses environmental burdens of products and processes right from materials extraction to disposal popularly referred to as cradle-to-grave or even cradle-to-cradle. For accuracy, the

power generation life cycle assessments should better characterize spatial and temporal characteristics[352]. A life-cycle assessment is regarded as an environmental assessment of all steps used in production and delivery whole goal is to present a holistic and inclusive picture of environmental impacts by considering all significant downstream “and upstream activities and their impacts [353]

3.19.3.5. Sustainability Measuring Indicators and Parameters.

This section is a summary of work published in the conference paper [29], and journal paper [3] . A sustainable electricity transition calls for eventual transition of 61.3% of the global electricity production to low carbon and renewable energy sources. In the short and to some extend middle term, natural gas can substitute oil and coal although with the risk of delaying the zero emissions transition and creating transition related carbon lock-in and stranded assets by developing natural gas infrastructure. Since countries with huge coal and oil reserves may find it unsustainable to make immediate transition, increase in the share of natural gas and investment in efficient technologies like cogeneration and clean coal technology can reduce the carbon footprint [148].

Sustainable energy transition should address the five major dimensions. They are technical, social, economic, environmental, and institutional dimensions. These dimensions of energy sustainability are summarized in Table 3-1.

Table 3-1: The five dimensions of energy sustainability

Dimensions	Features and Role	Parameters and Indicators	Impact/Effects
1 Environmental Sustainability	Concerned with managing the negative impact of energy production and use to the society and to	Emission levels for SO ₂ , NO _x , CO ₂ , particulate emissions, non-methane volatile organic compounds, land use and requirements, GHG emissions, environmental external costs, radionuclides external costs,	Seeks to maintain the integrity of natural environment and its ability to remain resilient

	magnify or extend the good ones	severe accidents. Life cycle emissions of GHG emissions in kg (CO ₂ -eq.)/kWh	and productive in support of humanity
2	Economic Sustainability	Measures the cost competitiveness of energy options. concerned with the viability of individuals and organizations, and energy products, and services	Operational stability, liquidity, net present value, cash flow, profitability, energy cost, cost of generation, unit cost of power, investment payback period, cost of capital, access to capital, affordability of power.
			Economic sustainability ensures that the energy or electricity system is economically viable and feasible and hence makes the investment attractive to investors and financiers
3	Social Sustainability	Concerned with the rights and voice of the people as measured by the level of social acceptance and access to the energy resource and systems by	Accountability, empowerment, respect for human rights, democracy, level of participation, respect cultural identity, people's resistance to intervention, and institutional stability and level of corporate social responsibility
			Energy project acceptance by the people and hence its implementation. Ensures that projects add value to the people and high human capital

	the people		and social capital. Seeks to increase people's benefits.
4 Technical Sustainability	Concerned with the ability to meet the current and future demand in a safe and efficient manner with the use of clean sources of energy and technology	Lifecycle duration, level of emissions, waste generation, recycling, waste disposal, system efficiency, exergy efficiency, primary energy ration, reliability, maturity, and safety. specific fuel consumption, specific emissions, availability, load factor, electricity price, fuel cost, demand and supply, operation and maintenance cost, power purchase agreements, plant life, lifecycle costs.	Facilitates continuous supply of affordable, accessible, and reliable electricity supply to meet current and future demand using state of the art conversion systems and technologies.
5 Institutional/ Political Sustainability	Puts in place effective institutions, policy and legal measures, regulations, control, and governance for sustainable energy.	Existence of effective supporting policies, legislations, energy regulatory institutions, utility companies, courts, government departments and ministries and power generating companies.	Affects quality of governance and investment in clean energy. Seeks to increase order, service and performance efficiency, output, and effectiveness in performance towards

From Table 3-1, it is noted that there are five dimensions of energy sustainability namely environmental, economic, social, technical, and institutional/political sustainability which can be used to design and analyses energy sustainability measures.

3.20. Sustainability of Power Plants

3.20.1. Technical Indicators

3.20.1.1. Reliability

The reliability of a power plant refers to its probability to perform appropriately for a given period without any repair during operation. Different power plants and specific designs have different degrees of reliability.

3.20.1.2. Capacity factor

Capacity factor is a ratio of maximum load of a power station to design capacity. It is an indicator of reliability and often affects cost of power with power having high-capacity factors like nuclear and geothermal being ideal for base load power supply.

3.20.1.3. Technology Maturity

The level of technology is a qualitative indicator that reveals the state a state-of-art of a given conversion technology. The level of technology can be classified as low technology maturity, i.e., only laboratory tested, highest technology maturity, i.e., commercially available with high market penetration.

3.20.1.4. Resource Availability

This is a measure of the energy resource potential of a country generally presented as TWh–yr for Hydro, PV, CSP and Wind. It represents the techno-economical feasible energy potential in terms of energy reserves.

3.20.1.5. Ability to Respond to Peak Load.

Ability to respond to peak and off-peak load is an important indicator in planning for generation mainly as qualitative parameter and quantitative in terms of time requirements to

load and offload. Hydropower, diesel, and gas turbine power plants generally have fast response to load changes and hence ideal for peak load applications. Power plants like coal, nuclear and geothermal have low response and hence ideal for baseload applications.

3.20.2.Environmental Indicators

This contents of this section is presented in publications [162] as book chapter on environmental impacts of energy sources and power plants. Energy production has several direct environmental challenges which include climate change, air pollution, water pollution, land contamination, thermal/heat pollution, and solid waste disposal. Energy related air pollution is a major environmental challenge facing urban areas. Fuel combustion leads directly to emissions and potential environmental harm, while use of electricity does not lead directly to environmental impacts, but its production from fuels leads to emits significant quantities of greenhouse gas emissions and other environmental impacts. However, if electricity is produced from renewable and low carbon sources like wind turbines, solar photovoltaic cells and nuclear has limited direct emissions compared to fossil fuels. Assessment of environmental impacts of energy carriers considers processes from resource extraction, its conversion into secondary energy carriers, consumption, and waste disposal or recycling [162].

3.20.2.1. Land Requirement

Land has economic as well as social implications making its requirements a serious input in energy system sustainability assessment. Some power plants like wind and large-scale hydro power have significant land and can lead to massive displacement of people and significant environmental and economic impacts.

3.20.2.2. CO₂, NO_x, SO₂ and CH₄ Emissions

Several power plants and energy resources release pollutants like SO₂, NO_x CO₂, CH₄, in different quantities at various stages of their life cycle. In this study, life cycle emissions for different sources were applied in the sustainability analysis [186].

3.20.2.3. Water Consumption

Water is needed at different phases of the lifecycle of a power plant. Some power plants have significant water requirements making water an important parameter in sustainability

assessment of power generation systems. Water is used for cooking, cleaning and for steam generation as a working fluid for Rankine cycle systems.

3.20.2.4. Lifecycle Emissions

The content in this section is published in publications [162, 186], co-authored by the supervisor Prof. Oludolapo. Lifecycle emissions are established by computing the global-warming potential of energy resources through the life-cycle assessment [162]. The values of life cycle emissions are presented in units of global warming potential per unit power produced. The scale applies the global warming potential unit, unit of electrical power, the carbon dioxide equivalent (CO₂e), and the kilowatt hour (kWh). The lifecycle analysis for fuels captures the emissions related to feedstock production and transportation, fuel processing and supply/distribution, and use of the finished fuel. The best fuel pathways to meet the GHG reduction thresholds is determined by comparing the sum of all lifecycle emissions for renewable sources of energy and direct emissions from the baseline petroleum fuel [162]. Life cycle impact assessment (LCIA) is part of life cycle assessment (LCA) whose is to evaluate and understand the magnitude and significance of environmental impacts for a product system across its life cycle [350]. Life cycle impact assessment involves characterization of impacts and selection of impact assessment categories based on their contribution to the normalized and weighted analysis results.

The environmental challenges emerging from the production and use of energy sources are well acknowledged today and includes global climate change, acidification of ecosystems, exposure to nuclear radiations, nuclear accident risks and public health effects from air pollution. Renewables offer significant promise in the reduction of environmental impacts of energy use because the technologies largely rely on natural energy and material flow cycles [162].

3.20.3.Economic Indicators

3.20.3.1. The Levelized Cost of Energy/Power Generation

The content of this section is published in journal paper and conference papers [23, 39] co-authored by the supervisor Prof. Oludolapo. The Levelized cost of power is a metric used to compare costs of power generation using conversion technologies usually USD/MWh. The metric involves determination data on all cash flows involved in its lifetime as well as on the

amount of electricity generated by the technology over its lifetime. The cash inflows from the project are recorded in aggregate form based on principles of monetary accounting that combine all cash inflows taking over the lifetime of the energy project. The various costs that are considered include power plant construction costs or capital costs, cost of operation and cost of maintenance. The costs that are not captured include taxes and subsidies and additional like integration of variable sources [176].

Levelized cost of energy/electricity (LCOE) provides an objective basis of comparison for weighted average costs of different power generation technologies facilitating the comparison of different technologies in a more accurate manner. The LCOE metric is however not equivalent to the amount of feed-in compensation or electricity price which includes other costs like taxes, subsidies and other incentives which may vary the final price or cost of power. Instead, LCOE serves as an adequate investment decision tool for individual power plants at the beginning of a project. The actual or exact value of the electricity is determined by among others, the hourly variations and weather-related changes which affect demand and supply conditions, and which cannot be substituted with LCOE metric.[354-358] .

The levelized cost of electricity (LCOE) is a metric used to compare costs of different conversion technologies in power generation on consistent basis. LCOE is analogous to the net present value of all lifecycle cost a power plant when divided by an a discounted total of lifetime energy output [359]. Levelized cost electricity represents the minimum constant price for which power should be sold for the operations to breakeven over the lifetime of the power plant. The computation of LCOE makes several non-financial assumptions plant availability, environmental impacts, among others [359]. The costs considered in computing the LCOE include construction costs, cost of capital, cost of operation and maintenance, fuel costs and disposal costs.

3.20.3.2. Input Data for Levelized Cost of Energy Analysis

The accuracy of the LCOE depends on the accuracy of input data used in the electricity project evaluation model. Inputs are usually deterministic in nature and represent a single figure. The application of probabilistic costing, by methods like Monte Carlo simulation are valuable. One challenge with increased penetration rates of renewable energy is that it reduces the market value, and while accomplishing the rollout is a challenge [29, 326, 360]. Therefore ,

energy economics has an significant role to play in determining the market prices of energy, and this is accounted for in systems analysis, since it affects project viability[361].

In its simplest form, the levelized cost of energy is expressed mathematically as.

$$\text{Levelized cost of energy (LCOE)} = \frac{\text{Total discounted expenses}}{\text{Total dicounted power generation}}$$

However, to compute the total discounted expenses and the total discounted power, requires various input values guided by the various applications and assumptions made in LCOE computation and complexity of the project [361].

The various data, variables, and assumptions in the computation of levelized cost of energy/electricity is shown in Figure 3-2.

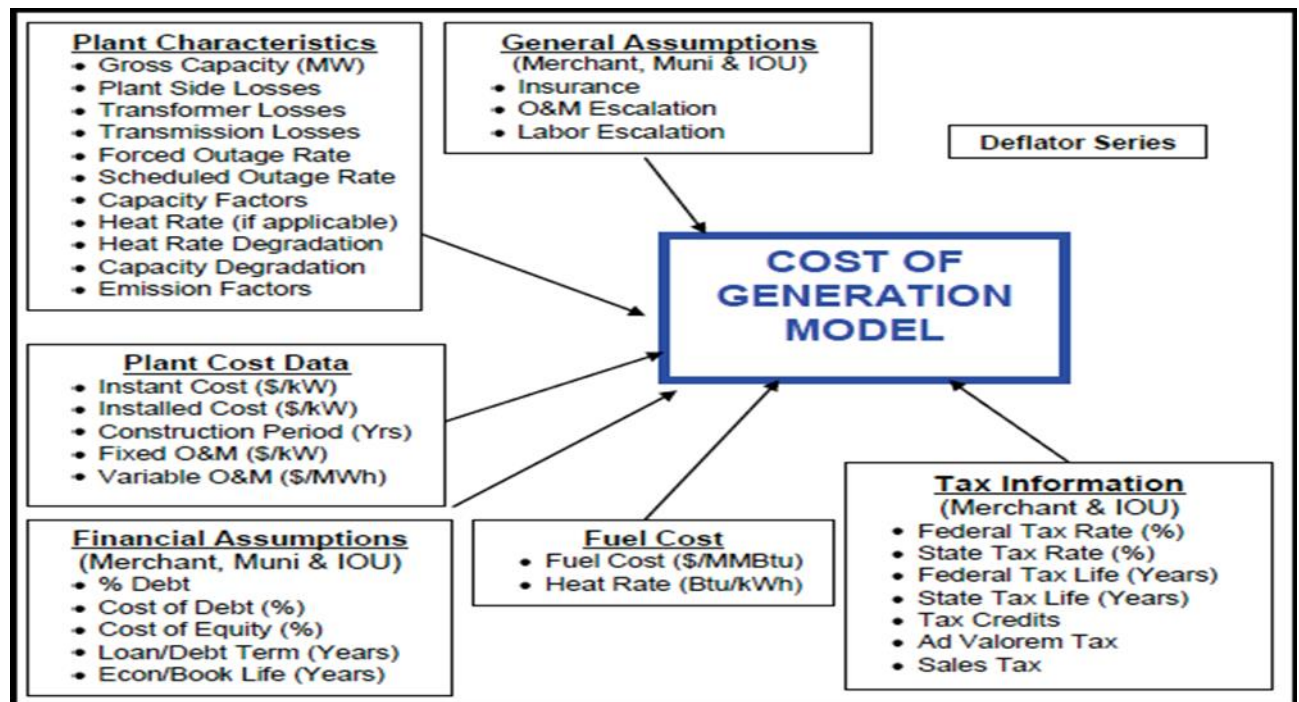


Figure 3-2: Input data and information for Levelized cost of Energy[39].

From Figure 3-2, it is noted that the use of LCOE requires a wide range of data for its computation or modelling. This includes data on plant cost like instant cost, installation cost, fixed operation and maintenance and variable operation and maintenance; financial data like debt percentage, cost of debt, terms of loans, economic life of the power plant; fuel costs e.g. heat rate and price of fuel; tax information like the federal tax rate, state tax, tax credits, sales tax etc; power plant characteristics like gross capacity, transmission losses, forced and planned

outage, heat rate degradation, capacity degradation and emissions factor; general assumptions like insurance, labour escalation, and escalation in operation and maintenance.

The complete LCOE, is also called ‘cost of generation’, involves the use of many input variables as demonstrated in Figure 3-2. The summary of most common relevant inputs including power plant characteristics, cost of plant, assumptions on finance and operating conditions, fuel cost, and tax details should be available as project information, or from state and industry sources. A breakdown of the costs per energy source and conversion technology can distinguish between capital costs, fixed operations and maintenance, and fuel costs. renewable technologies like wind, solar and hydro have almost nil fuel costs. Fuel cost is a major input for fossil fuel sources like coal, gas, and coal power plants [279, 280, 361].

3.20.3.3. Component elements of Levelized Cost

Levelized Cost of Electricity (LCOE) is an economic metric used in comparing lifetime costs of power generation from different technologies [362]. These costs can be classified as capital, operation and maintenance and disposition costs:

i.) Capital Costs

Capital costs are up-front costs used to build and commission the power plant a power plant ready for operation and maintenance. These costs alone do not paint a clear picture of the total costs needed for analysis [363]. Figure 3-3 shows the capital costs of some renewable energy sources [362]

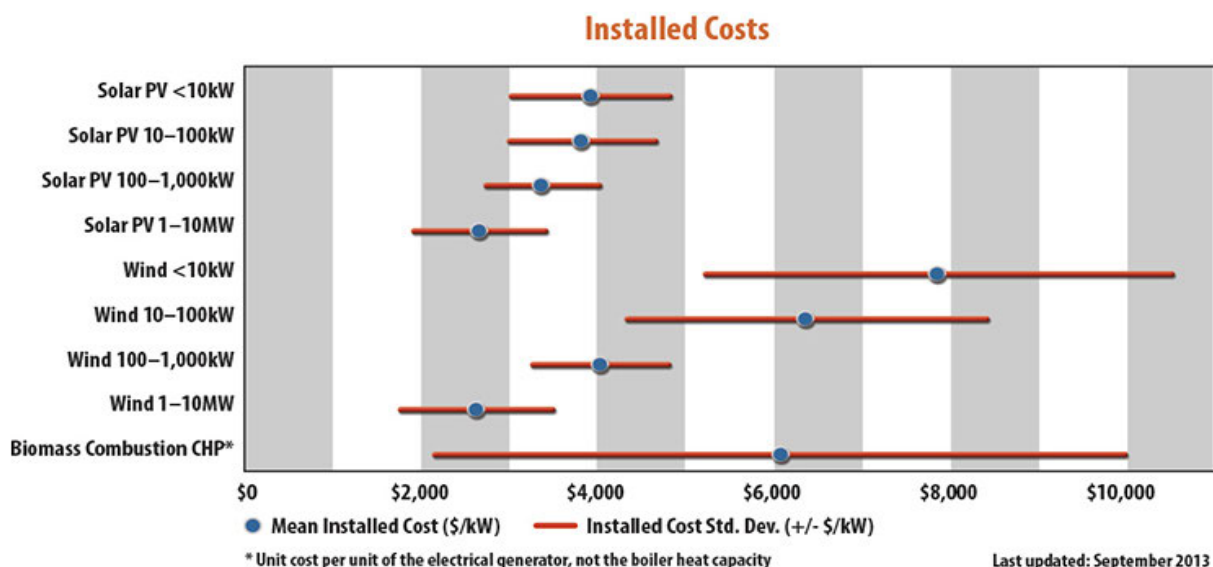


Figure 3-3: Upfront costs of some renewable sources [39, 363].

The real and estimated costs of power plants tend to vary significantly. Real-life costs can diverge significantly from those estimates. Capacity factors can also be used to compare power plants and can be as low as 10-20% for some wind and solar applications, up to 50% range for offshore wind and as high as 90% for the most reliable nuclear and geothermal power plants [78, 109]. The average capacity factor of all commercial nuclear power plants in the world in 2020 was 80.3% which is less than the 83.1% for 2019. This value however includes outdated Generation II nuclear power plants. Although peaking power plants have low capacity factors, they compensate by charging highest possible price when they supply power [364].

ii.) Operation and Maintenance (O&M) Costs

The operation and maintenance costs are costs incurred in the running of a power plant for power generation. These costs can be classified into fixed and variable costs. Fixed O&M costs include employees' and security which must be incurred whether the power plant is operating or not while Variable O&M costs are linked to generation output e.g. fuel costs and therefore they vary with output [362].

The operation and maintenance costs take the form of fuel expenses, cost of plant and system maintenance, cost of power system operation, cost of storage, and plant decommissioning. Fuel costs are highest for oil fired plants followed by coal, gas, biomass, and uranium. Because of high energy density of uranium (or MOX fuel in plants that use this alternative to uranium) and the comparatively low price on the world uranium market measured in units of currency per unit of energy content, fuel costs only are just a fraction of the operating costs of nuclear power plants. The cost balance between capital and running costs favors lower operating expenses for renewables and nuclear and in the other direction for fossil fuels [362].

The cost of generation for oil fired gas and coal power plants are significantly affected by the fluctuations in fuel prices. Since renewable sources have no fuel cost, they are not affected by the fluctuations in the world markets. Coal plants using low grade lignite having high moisture content incur high transportation costs. The economic viability of a carbon tax and other forms of CO₂-pricing, significantly affects the economic viability of fossil fuel-based power generation. Nuclear power plants are not affected by fuel cost fluctuation mainly

because of the industry practice of Uranium stockpiling and less frequent change of fuel or refueling. Most Pressurized Water Reactors have the fuel change for a third or a quarter of their fuel loading usually every 18 to 24 months. It is also a common practice in the industry for uranium fuel suppliers bear the cost of short-term price fluctuations in uranium prices instead of passing to power plant operators except for the case of long-term price trends which may affect the final price of nuclear electricity [362].

Wages and salaries constitute a significant cost item for both nuclear and renewable energy whether the power plant is operated at full or part load capacity of its nameplate capacity. In France, nuclear power supply accounts for about 70% of electricity demand, hence nuclear power plants operate on the load following mode for the purpose of achieving stability. The withdrawal of subsidies in Germany for wind power plants aged 20 years and above led to the forced shut down because the market-rate of electricity price of some €0.03 per kWh was not enough to cover the marginal costs, or they only covered the marginal costs when there was no major maintenance for the power plants. Nuclear power plants that had been fully depreciated but remained in operations proved to be highly profitable between 2010s and early 2020s even by operating without state subsidies [362].

iii.) Disposition Costs

Disposition costs of a power plant are typically incurred in disposing of the power plant at the end of useful life. Disposition costs are particularly huge for nuclear power plants in terms the disposal of radioactive materials. The scrap value of the equipment should generally cover the removal cost hence a net of zero may be assumed for many power plants [362]

The levelized cost of energy is computed by first considering the net present value of cost of building and operating the power plant then dividing by the total lifetime electricity generation [365]. The various elements of total used are.

- i. Initial investment cost of the project (I)
- ii. Operation and maintenance expenditures (M)
- iii. Total fuel costs incurred if applicable (F)
- iv. Total power output for the project lifetime: The sum of all electricity generated (E)
- v. The discount rate of the project (r)
- vi. The life of the system (n)[365]

$$\text{LCOE} = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}}$$

$$\text{LCOE} = \frac{\sum \frac{(I_t + M_t + F_t)}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}}$$

$$\text{LCOE} = \Sigma[(I_t + M_t + F_t) / (1 + r)^t] / \Sigma[(E_t / (1 + r)^t)] [365]$$

Energy produced can consider the depreciation rate of the plant and equipment [5]. The formulation is here given just as an example of classical LCOE:

$$\text{LCOE} = \frac{\text{CAPEX} + \sum_{t=1}^n \frac{\text{OPEX}(t)}{(1 + \text{WACC}_{\text{nom}})^t}}{\sum_{t=1}^n \left[\frac{\text{Utilisation}_0 * (1 - \text{Degradation})^t}{(1 + \text{WACC}_{\text{real}})^t} \right]} [\text{€}/\text{kWh}] \quad (1)$$

Equation (1) is the formula for Levelized cost where ;

CAPEX is investment cost for year $t = 0$,

OPEX(t) is the cost of operations and maintenance for year t ,

WACC_{nom} denotes the nominal weighted average cost of capital per year,

$\text{WACC}_{\text{real}}$ is actual or real weighted average cost of capital per year,

Utilization applied is the initial utilization for year, $t = 0$ (where degradation is not applied).

Degradation is the annual depreciation or degradation of the nominal power of the system,

n is the economic life or lifetime of the power plant or power system, and it represents the year of lifetime.

For a variable renewable like solar energy and solar power plants, additional generation related costs are insurance costs, the tracking factor which converts solar energy resources to real incident solar energy, and a performance factor which converts the total available solar resource into the real amount generated electricity by the system per Watt installed [5, 366].

Table 1 demonstrates the levelized cost of various energy sources based on Lazard's analysis [362].

From the publications [23, 39], it was concluded that. Power generation incurs different costs that can be classified into capital costs, wholesale costs, retail costs, and external costs depending on applications. The Levelized Cost of Energy (LCOE) is a standard tool applied in cost comparison of electricity generation or conversion technologies expressed as the total cost of energy/electricity produced by a power plant over its entire useful life. The levelized cost of energy or electricity (LCOE) is a model used to estimate the cost of electricity before the powerplant is constructed. The metric presented as a single value to represent each generation option in a particular location for easy comparison by investors or policymakers involved in planning and decision making. However, although the standard LCOE metric is widely accepted in comparing power generation projects globally, modifications in terms of variations can be applied to capture factors like inflation and the Levelized profit of energy and some variable costs. There is need for accurate analysis and due diligence when accounting for limitations of levelized cost of energy metric especially when making decisions concerning economic, environmental, and social, impacts. The main limitation of levelized cost of electricity/electricity is that it ignores the cost of intermittency associated with variable renewable sources like wind and solar [39].

3.20.3.4. Levelized Cost of Storage.

Information on the levelized cost of storage of power plants is presented in publication [39] co-authored by the supervisor Prof. Energy storage is an function in in low-carbon electricity systems used for balancing intermittent and inflexible of supply with demand [367]. Electricity storage is currently the most flexible options to increase the flexibility of an electric power system because of its ability to generate and consume electricity, compared to demand-side response (DSR) or flexible generation, and ability to shift power supply. Bulk energy storage plays an important role in the energy transition by increasing flexibility of the power system and hence uptake of flexible renewable sources, like wind and solar which are critical for the low carbon grids.[368]. The cost of various storage technologies vary with different application scenarios and technology used [324]. Storage systems with longer service life and mass produced like Lithium-ion tend to be lower.

Electricity storage capacity is projected to increase from 145 GW in 2010 to 266 GW by 2030 globally, indicating its significant in power generation and suppl. In costing terms, the Levelized cost of storage (LCOS) is analogous to LCOE but is applicable to energy storage technologies[5, 369]. Storage is considered as a secondary source of electricity whose value depends on the primary source of power generation. A fair cost accounting requires that the costs of both primary and secondary sources be considered when storage cost is considered in real time power supply scenarios [370]. Energy storage is characterized by inherent inefficiencies and hence higher CO₂ emissions if any component of the primary source is less than 100% carbon-free.

Levelized cost of storage refers to the total lifetime cost of the investment electricity storage technology divided by its delivered cumulative delivered electricity[371-373]. The value of energy storage at macro level is higher if it contributes to realization of system objectives like increasing economic value, reliability, and sustainability of the power system. For most energy models, sustainability and reliability are forced by constraints, and with energy as an exogenous factor, this cost becomes the main metric for economic value. The traditional approaches for storage technologies improvement seek to reduce their costs, but the cheapest energy storage is not always the most valuable for power systems [374].

The Levelized cost of storage is therefore taken as an internal average price that electricity is sold for the investment's net present value to be zero which makes it analogous to the to the concept of Levelized cost of energy/electricity (LCOE) for conventional power generation technologies. Although the Levelized cost of storage (LCOS) Levelized cost energy (LCOE) for generation technologies can be directly compared, different concepts ae used to provide electricity leading to some differences in cost computation and hence the use of different names for the two approaches to power generation [368, 369].

3.20.4.Social Indicators

3.20.4.1. Job Creation

The jobs created by a technology has significant influence project acceptance and generally refers to the lifetime jobs created by a given power generation technology at various stages of the lifecycle e.g., design, construction, manufacturing, installation, operation and maintenance and processing of fuels.

3.20.4.2. Safety Risks

Safety concerns and features are important considerations in decision making during formulation of energy policy through sustainability assessment. Safety issues are a combination of both quantitative like history of fatalities and qualitative like public opinion or perception e.g., public approval and perception is low against nuclear energy and power plants.

3.20.4.3. Social Acceptability

Social acceptance is a qualitative indicator established by consultation with local community to get their views. Qualitative values and scale applied in previous studies were adopted for use in this study. Documented values for public attitudes towards different energy sources and conversion technologies were applied in this study.

3.20.5. Institutional Indicators

The energy transition is difficult to achieve without political interventions, with intervention having new and often unforeseen consequences which ought to be identified. at planning phase to assess them. It is important to identify the possible benefits and limitations of different energy and climate policy initiatives and compare proposed alternative courses of action to make trade-offs and alternative options at the early stages of energy projects.

Institutional indicators are used to assess the availability and adequacy of the institutional framework needed to sustain effective and efficient energy system. Institutional indicators link and address response actions and policy measures designed to influence trends in the social, economic, and environmental dimensions. The institutional indicators can be used to determine existence and effectiveness of a national sustainable energy development strategy or plan, existence of energy statistical capacity, analytical capabilities, and the adequacy and effectiveness of investments in capacity building, education or research and development.

Institutional indicators help monitor progress to the right and effective legislative, regulatory and enforcement measures for efficient energy systems. Institutional indicators tend to address issues that are difficult to quantify and most of the issues are future oriented hence they require dynamic analysis based on energy investment, generation and use projections,

The institutional variables also tend to structural or policy responses to sustainable requirements.

3.21. Sustainability Assessment of Energy Sources

Sustainability assessment of energy sources involves the analysis of the energy and power plant sustainability indicators to identify sources of energy and conversion technologies and power plants that offer the optimal solution within the five dimensions of energy and power sustainability. Figure 3-4 illustrates the sustainability assessment method with indicators for various energy sources.

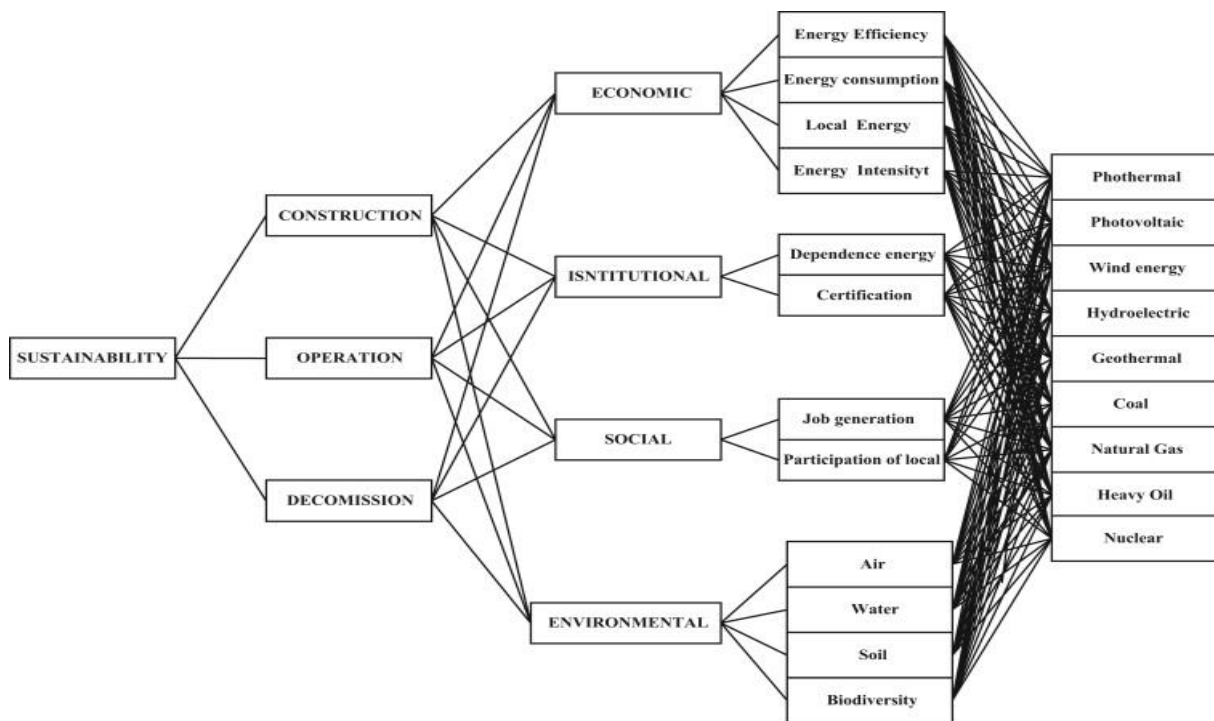


Figure 3-4: Sustainability assessment dimensions and indicators (by the authors)

Figure 3-4 summarises the indicators for the main social, institutional, environmental, economic over the life cycle through construction, operation, and decommissioning phases.

3.22. Generation Planning

3.22.1. Electricity Demand Forecasting and Generation Planning

Customers expect a least cost and high-quality power supply in competitive electricity markets, which requires additional investments and more sophisticated operation techniques to enhance reliability and security of supply. Severe consequences which may otherwise arise in

the event of cascaded by system sophistication[375].Secure operations is always paramount for economic operation of power systems. A power system should have sufficient degree of security margin, to avoid being exposed to severe and, in some cases, catastrophic system failures[375]. The traditional generation planning approach requires planning for a sufficient firm generating capacity to meet electricity demand and other system technical and reliability requirements followed by developing such firm capacity generating base, absorb the non-dispatchable generation to the optimum level to supplement firm capacity to cater for other requirements like fuel diversity and economics [252]

3.22.2.The load Curves.

The load curve is a primary tool used for economic analysis of electric utility operations and planning new energy systems and generation. Piecewise linear approximations to the load duration curve is needed in general equilibrium models and also in other models using linear programming [376].

The load on a power station varies from time to time and is never constant. The load variations are often, noted on half-hourly or hourly basis and are plotted against time on the graph. This curve that shows the variation of load on the power station with respect to time is the load curve. A daily curve is obtained over a span of 24 hours while a monthly load curve is obtained from the daily load curves of the whole month. It is the monthly load curve is that is generally used to fix the energy rates. An annual load curve or the yearly load curve is obtained from monthly load curves of that particular year. The annual or yearly load curve is used to determine the annual load factor [376].

Load curves provide information and help planners in making decision on the size of installed generation capacity of the power station as well as well as the economical sizing of the various generating units within power plants or power systems. Load curves enable the estimation of generating cost and decision making on the operating schedule or sequence of operation of the of the power station terms of which units should run and for how long [377].

The load on a power station is not constant, instead it continuously varies based on customer demand. The load curve is a is a graphical representation of varying load demand on a generating station normally recorded at half-hour or hour intervals against the time chronological order as shown in Figure 3-5.

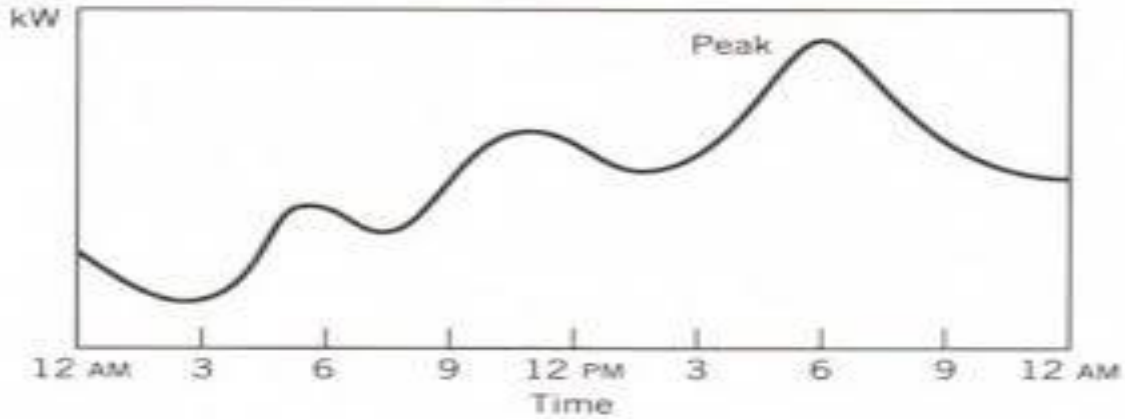


Figure 3-5: The load curve.

Figure 3-5 demonstrates a typical daily load curve. From the load curve, the following information can be generated.

- i. The area under the load curve is the total energy generated by a power plant. Therefore, units generated/day = Area (in kWh) under daily load curve.
- ii. Dividing the area load curve, by the rectangle in which is contained give the load factor of the power plant.
- iii. The maximum or peak value on the load curve is the simultaneous maximum demand on the power station.
- iv. Average demand on a power station is the area under the curve divided by hours of the day.
- v. The load curve can be used to establish the minimum load on a power station.
- vi. Load curves can be used to compute the minimum, maximum and average load as well as average annual load factor. $\text{Load Factor} = \frac{\text{Avg. Load}}{\text{maximum Load}} = \frac{\text{Avg. Load} \times 24}{24 \times \text{maximum Load}}$
- vii. The daily, weekly, monthly load and annual curve for a power station is unique, hence it differs every day, week, month, and year.
- viii. The load curve provides information for preparing the operation schedule of the power plant.

- ix. The load curve facilitates the selection and sizing of future power plant generating units to efficiently supply variable and fixed load demand.

3.22.3. Load Duration Curve

The load curve is generally used hand in hand with the load duration curve in planning for current and future generation needs. The load curve accurately reflects the activity consumers in terms of electricity consumption over a given period. A load duration curve (LDC) is quite similar to the a load curve except that data is presented in descending order of magnitude, instead unlike the chronological order presented in the load curve. It indicates the capacity utilization requirements for each load increment.

A load duration curve is obtained when the load elements of the curve are arranged in descending order of their magnitude hence the maximum load is arranged on the left and the lowest on the right in descending order. The same data source is used to develop both the load curve and load duration curves. The area under the load curve and that under load duration curves are equal [376, 378]. The height of a slice represents capacity, while the width of the slice represent capacity utilization rate or capacity factor while the product of the two is a measure of energy produced [377], [379]. The LDC and LC are demonstrated in Figure 3-6. below.

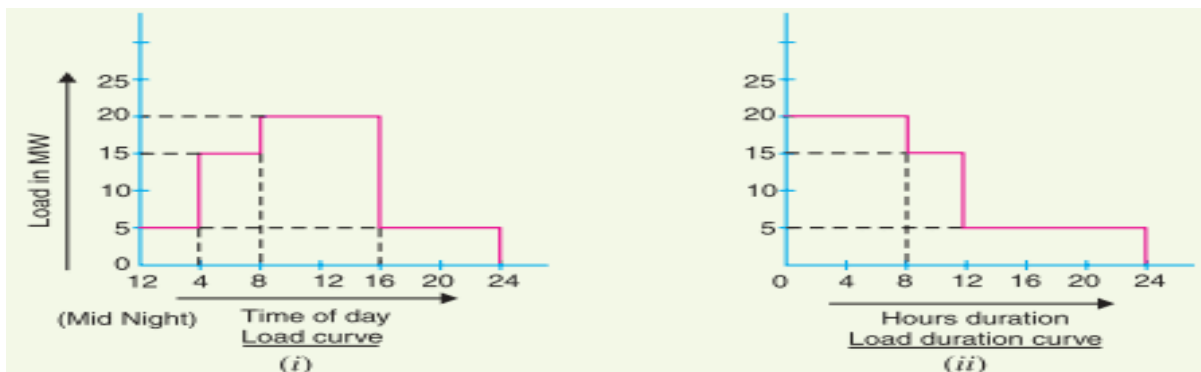


Figure 3-6: Load curve and load duration curve

From Figure 3-6, the following points may be noted about load duration curve:

- i. The load duration curve provides the data in a more presentable forms in terms of number of hours during which load prevailed.

- ii. The area under the load curve and that under the load duration curve are equal and are expressed in kWh representing units of electricity produced.
- iii. The daily load duration curve to include period e.g., week, month, or year.

The load duration curve provides information on the amount electricity consumed over given period. The load duration curve is a graphical presentation of the load on power plants and energy produced in in kilowatts with area under the curve in LDC providing an indication of energy demanded. Loads in the LDC are arranged in sliding order of their magnitude. The LDC chart provides an indication on the efficiency of power grid [380]. In power generation, the LDC shows the relationship between generating capacity requirements and capacity utilization of a power system with demand data presented in the descending order of magnitude. Figure 3-7 shows a typical load duration curve.

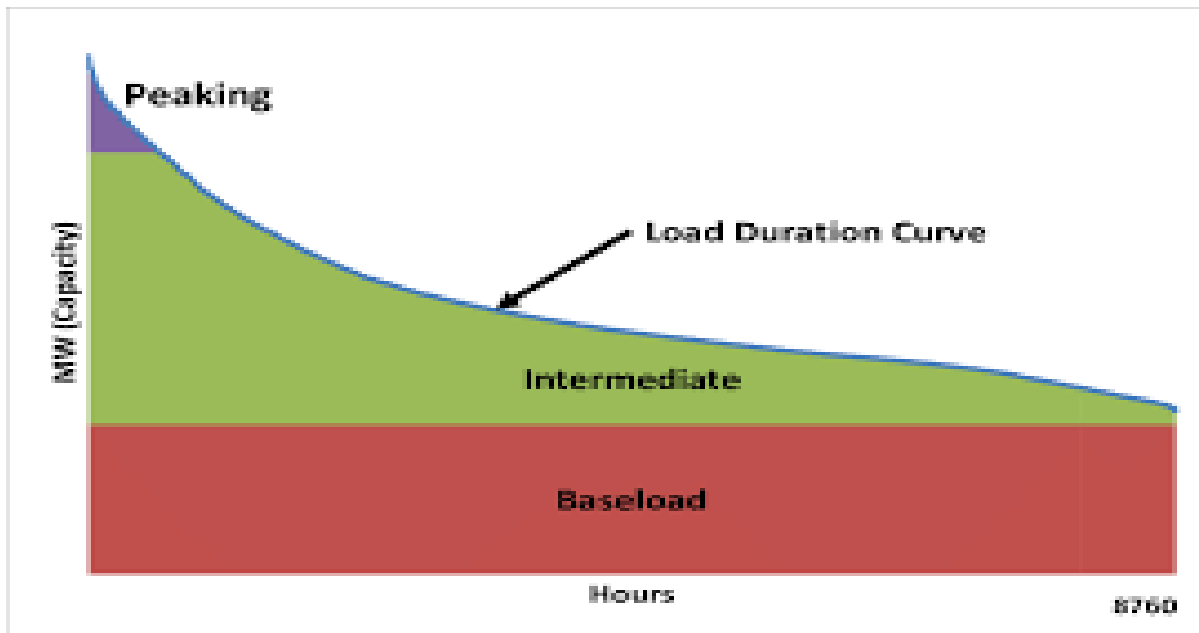


Figure 3-7: Load duration curve

Figure 3-7 shows an annual load duration curve covering 8760 hrs. The area under the curve is divided into the base load, intermediate load, and peak load.

i.) Base Load Generation

Base load plants supply a steady load demand and are expected to be available and to run 100 per cent of the duration. Base load power usually planted account for about 40% of maximum

load. Power plants ideal for use as base load include base load are nuclear power plants, hydro and coal fired power plants [380].

ii.) Intermediate Load Following Power Plants.

Intermediate load power plants operate throughout the year just like base load power plants. Compared to base load power plants, intermediate load power plants have ability to slope up and down rapidly in response to change in demand throughout the day. Examples of intermediate load power plants are the combined cycle natural gas plants and hydro power plants [380].

iii.) Peaking Load Power Plants

Peak load power plants operate for short durations whose applications include emergency and peak power supply. The peak load power plants generally account for 15% of the peak load. Examples of peak power plants are the gas turbine power plants, hydro power plants, diesel power plants and gas turbine power plants [380].

The LDC concept is well suited for use in probabilistic techno-economic analysis such as Monte Carlo simulations. The results are presented of Monte Carlo simulations of implementation scenarios of distributed generation technologies (DGT) at CI and industrial customer sites using HQ electricity rates [86].

The shape of the load duration curve (LDC) has direct influence on the mix of power generation technology selected. Reduction in peak demand reduces the demand for thermal power plants hence less gas, oil or coal consumption. When the load duration curve flattens, the base load thermal plants operate more efficiently. Peak load power systems are found at the highest magnitudes followed by the intermediate load and then at the bottom of the load curve is the base load hence the load demand curve assists in evaluation of system reliability. It also assists in economic dispatch and planning [86],[380].

Figure 3-8 shows the relationship between the load curve and load duration curves.

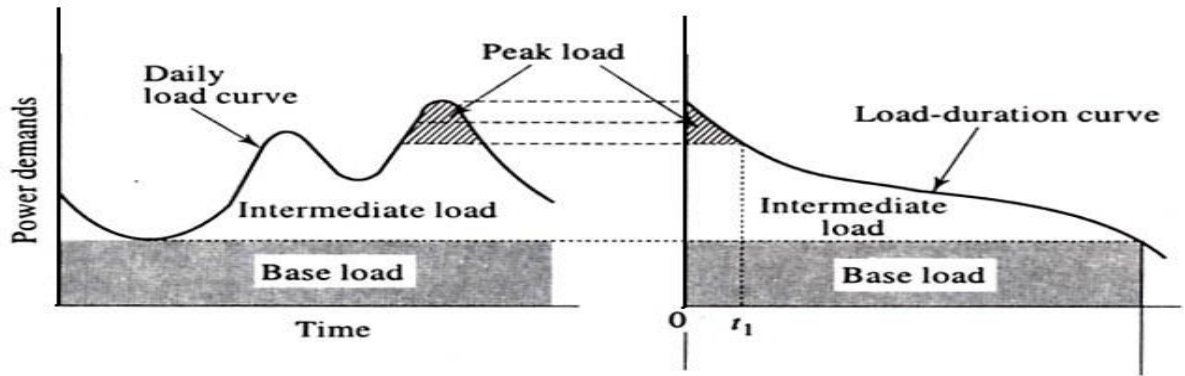


Figure 3-8: Load duration curve and its relation to generation technologies.

From

, it is noted that the load duration curve, provides a graphical representation, of the demand on power supply stations throughout the day making it a useful tool in capacity and generation planning to realise economic power generation. It facilitates decision making and scheduling of power plants for power supply i.e., how, when and in what sequence to load and offload the generation units and power plants. At the valley, or lower load demand some units must be shut down and restarted as demand rises.

3.22.4. Dispatch

The main objective in power generation is to produce required amount of power at minimum cost with minimum power losses. In economic load dispatch, the generator's real and reactive power vary within certain limits to meet a particular load demand at minimum fuel cost. Load allocation in a power system is based on some constraints[381]. In the allocation, renewables prevail over fossil fuels as clean energy source and their penetration in the power sector is increasing. However, the intermittent nature of these renewable energy based-power generation is a threat to grid security and stability. The intermittency can be handled by the integration of distributed energy resources [89].

3.23. Fixed and Variable Load

The load on a power station keeps varying because the consumers demand is not constant, and a power plant is designed to meet the varying load requirements of the consumers. Therefore, a power station never encounters a steady load in actual practice. Different consumers require small or large block of power based on the demands of their activities. The demand of

one particular consumer at any time is different from that of the other consumers and the demand may come at different times even for same electrical equipment which leads to load variations on the power station from time to time.

3.23.1.Effects of Variable Load:

The variable load on a power station leads to the following consequences.

i. Need of Additional Equipment

Existence of variability in demand necessitates additional equipment e.g., air, coal and water whose supply has to be varied to produce variable power. Increase in demand leads to increase in fuel, water, and air supply to the boilers to meet the demand increase, hence additional equipment must be installed for extra capacity. Modern power plants have extra equipment devoted entirely to for variable load supply.

ii. Increase in Production Cost.

Variation in load affects generation efficiency with reduced efficiency at part loads which leads to higher cost of generation. An alternator generally operates at maximum efficiency near its rated capacity; hence use of a single alternator will lead to poor efficiency at light loads on the plant. Therefore, in actual practice several alternators and individual sizes is such that they operate close to full load capacity. As load drops from peak, units are offloaded to such those in operation are matched to demand while operating close to their design capacity.

3.24. Dispatch Curve

A dispatch curve is a graph representing variable operating costs for power plants within a power system. The power plants are in ascending order of cost, leading to which indicates which resources are expected to be dispatched at various levels of varying load. Figure 3-9 shows a typical dispatch curve.

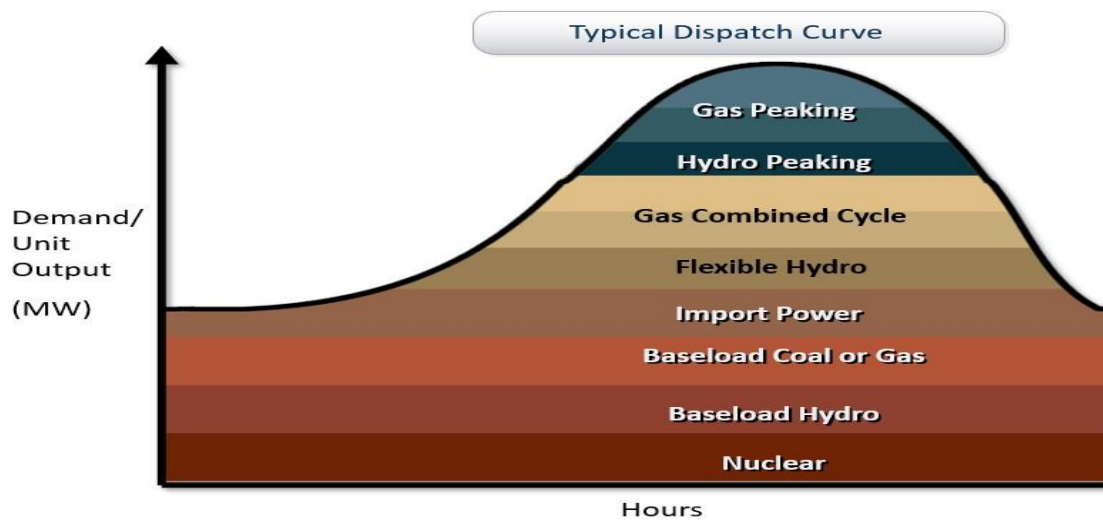


Figure 3-9: Dispatch curve of a typical power system

Figure 3-9 demonstrates a typical traditional dispatch curve. It is noted that base load power station is at the base starting with nuclear, hydro, coal, or gas, import power, flexible hydro, gas combined cycle, hydro peaking, and gas peaking in that order.

There is need to develop efficient methods of forecasting electricity load-duration curves and load curves for accurate planning and dispatch of power plants. The approach is to first forecast the load curve then apply the results of the load curve to forecast the load-duration curve. Same models can be used to predict both load curves and load-duration curves can be, and confidence intervals can be generated in either prediction. An accurate load curve can be predicted is based on half-hourly data or even less. An effective model should, or forecasting should capture effects like daylight savings, holidays and weekends, and trends annual, weekly, and daily cycles. Time-series methods, like Kalman filtering, smoothing and prediction can be used to fit the model and to achieve the desired forecasts for load-duration curve [2].

3.25. Energy and Grid Based Modelling

This section presents information contained in conference papers[120, 121] and manuscript [382]. Energy system models have become the main supporting tool for energy policy. Modern challenges in energy planning and management require energy systems models that integrate technical, environmental, and societal aspects of the energy systems [382]. The energy transition will greatly be facilitated by information technology, smart technology and

smart energy systems, policy measures, market instruments and effective planning and optimization models[21, 25]. The energy systems Modelling has been to provide insights and strategies to plan a carbon-neutral future. Effective energy transition plan implementation faces multiple challenges ranging from integration different energy carriers and sectors to considerations over multiple spatial and temporal resolutions [383]. Energy models are simplified replicas of real-world systems and may contain some hard- or soft-linked sub-models. The use of Model generators facilitates the development of models by application of pre-defined equations like sets of equations representing a storage unit and converter. The term modelling framework refers to a structured toolbox that may consist of sub-frameworks and model generators [384].

Integrated energy system models create a representation of the various interactions between environment, resources, technology and investment, and economy and society. It is in the 1970s that the development of the first energy system models started. The International Energy Agency (IEA) through the Energy Technology Systems Analysis Program (ETSAP) first produced the MARKAL (MARKet ALlocation) modelling platform while the International Institute for Applied Systems Analysis (IIASA) developed its Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE). These very first models were both originally designed for bottom-up optimization of large-scale energy systems of countries or at an international level. These models require extreme simplifications such as country level aggregated values and seasonal or annual supply and demand balance ideal for base load and fully dispatchable generators. The temporal variability of renewable energy sources (RES), render the traditional tools not fully able to capture the complexity of current and future energy systems making it necessary to apply a power-based perspective of future energy system [384, 385]. Figure 3-10 shows the complex nature of energy modelling environment.

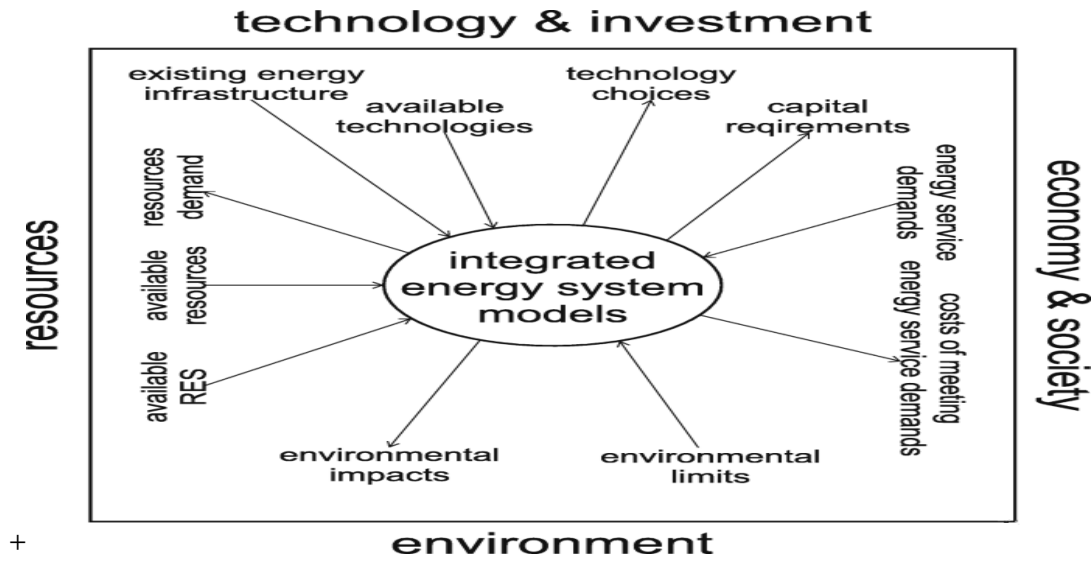


Figure 3-10: Integrated energy systems modelling[39].

Figure 3-10 is a pictorial representation of the interactions between environment, energy resources, technology and investment, economy, and society in an integrated grid-based MES model.

Power generation requires integrated, grid-based MES for three main reasons:

- i.) For the decarbonization of the global energy system, through substitution of fossil fuels by renewable electricity
- ii.) For the integration of fluctuating renewable energy sources (RES) is which remains a challenge for the electricity grid and
- iii.) To ensure better utilization of volatile renewable energy sources (RES) and existing grid infrastructures.

Most energy system models and modelling frameworks are opaque black or grey boxes, but this has changed as several public release of many models and modelling frameworks with free access. When compared with proprietary models and modelling frameworks, in open-source energy modelling, all the stages of the process open and transparent. The advantages of these models include improved quality of science due to increased transparency and reproducibility, more effective and broader collaboration, increased productivity due to sharing of the burden and profound relevance to social debates. It is for these reasons among others that this study adopted the use of free access models with a focus on the future energy and electricity systems where the concept of smart energy systems is adequately addressed.

Energy system modeling begins with careful identification and selection of the system boundaries to adequately assess the overall system. For MES, all energy carriers ranging from extraction to services are captured in system boundaries. An energy system includes ‘all steps in the chain all the way from primary resources to energy services.

Multi-Energy-Systems (MES) approach requires holistic consideration of an energy system, covering the energy stages from the extraction and treatment (e.g., gas well, coal mine, sun) to the services (e.g., heating, illumination, transport), without neglecting other carriers e.g., electricity, natural gas, oil, coal.

This study focuses on the grid-based energy carriers of the energy sector in the range from primary energy to final energy. There are four categories to characterize MES: spatial, multi-service, multi-fuel and network, where multi-service means that one energy source can supply energy services at the same time (e.g. a combined heat and power plant), multi-fuel implies that different services can be served by multiple primary energy carriers e.g. domestic heat can be produced by a heat pump or a gas boiler., while the spatial category caters for spatial resolution of a MES models, with common resolutions being a buildings, cities and entire countries. Energy networks should be designed to overcome the spatial distance between consumers and producers and facilitate development of multi-energy technologies and their interactions. Time resolution should also be considered in models that integrate variable RES and energy storage.

The energy sector covers various levels like energy extraction and treatment, energy conversion, and distribution to end users by the grid or off grid solutions. The flow of the various energy carriers through the energy system is illustrated in Figure 3-11.

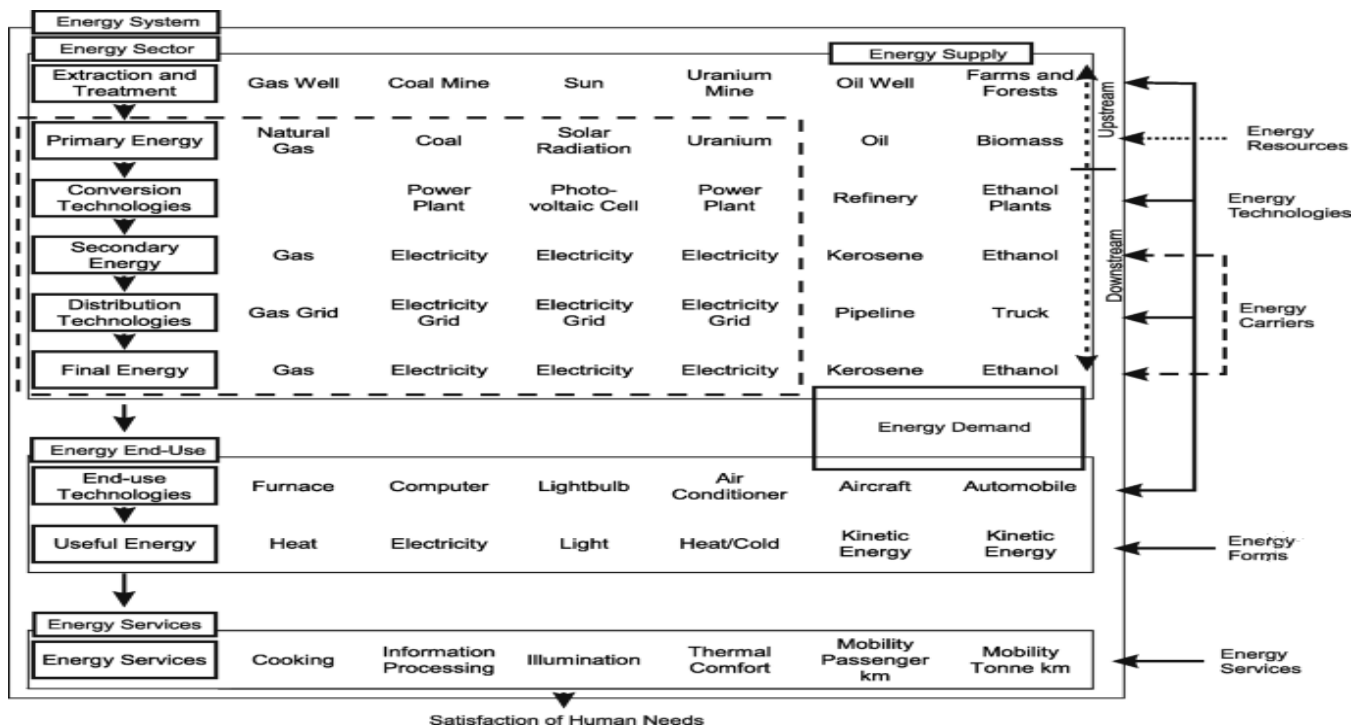


Figure 3-11: Schematic of the energy system, energy sector, energy end-use and energy services [382].

From Figure 3-11, the boundary is not fixed but for these demonstrations, the system boundaries are enclosed by the dashed box.

Planning and operation are the two most common modelling scopes, where planning models are used to evaluate the long-term evolution of the energy system, while operational models are used in the assessment of operational soundness of energy scenarios. The time horizon is particularly important for energy planning models since it determines the extend into the future that a model looks. Multi energy systems (MES) generally range from a single building to districts, regions, cities, or whole countries which is discussed or described in the spatial coverage influences the level of detail and the necessary computational effort is influenced by the mathematical model formulation and with the programming technique applied. Data availability is essential for detailed models because quite often, it may not be known or is of bad quality and not quite reliable. It is the level of details that dictate how thoroughly the physical properties of a given component e.g., part load efficiencies, power flow models are considered within the model. The spatial resolution is the main factor influencing the aggregation and network representation. The temporal resolution is important for the

integration of variable RES and influences the extent of consideration of short- and long-term dynamics.

The MES modelling approaches may be full and hybrid concepts. The full approaches consider all available energy carriers, but hybrid approaches consider just a few. Different degrees of detail are provided by different energy and power flow representations in electricity, gas and district heat networks ranging from simple network flow models to more detailed power flow representations like AC and DC load flow models.

The major requirements for grid-based MES include the possibility to model multiple energy carriers, a spatial resolution to model energy or power flows, a temporal resolution to model the short- and long-term dynamics of RES, and suitable network or power flow representations. The main challenges facing general modelling aspects include, data availability, data quality and increased model complexity due to modelling data uncertainty or human behavior while specific challenges are faced during representation of time and space in the model.

3.25.1.MES Modelling Aspects and Assessment

All models generally have some limitations, but some are more relevant and useful based on modeling objectives. It is necessary to model the values that are relevant to the problem and not those which lend themselves to modelling to get useful result from a model.

The Top-down (or macroeconomic) and bottom-up (techno-economic) are the most typical energy system modelling approaches today. Top-down models attempt to provide a holistic perspective of the economy including economic growth, employment, trade, etc. although they only consider the energy sector in a simplified and aggregated manner. On the other hand, the bottom-up models incorporate more technological details and apply economically driven approaches for evaluating technologies being investigated which enable them to provide more detailed future outlooks in terms of supply, demand, and possible technologies. However, higher technological details of the bottom up models require extensive data necessitating application of many assumptions with regard to technology diffusion, investments and operating cost [384]. The modelling grid-based energy systems needs a high level of technological detail which makes the bottom-up modelling approaches attractive for grid-based planning.

3.25.2.Modelling Scope

Long term energy systems evolution is investigated using energy planning models by considering investment decisions and accounting for changes in future parameters e.g. availability of fossil fuels, availability and access of renewable resources, cost of technology, the diffusion of technology and future learning. Since these parameters are input variables for energy models requires that they should be chosen carefully to avoid biased and inaccurate results. MARKAL/TIMES and MESSAGE are typical energy planning models applied in energy-based perspective working with highly aggregated data like annual demand and supply values. On the other hand, PLEXOS, GTmax and EnergyPLAN are typical operational models used to examine operational feasibility of scenarios. These models need a power-based perspective since energy demand must be met at any time of the investigated period. These models consider a consideration of the short- and long-term energy supply and demand dynamics in addition to technological, regulatory, economic and social constraints [384].

3.25.2.1. Planning Time horizon

The time horizon is related to modelling scope with common time horizons for planning model ranging between 30 to 50 years, while typical investigation periods for operational models is often between a day and a year.

3.25.2.2. Spatial Coverage

Spatial coverage of a model may range from a local, single building to districts and countries. Spatial coverage impacts on suitable programming techniques, level of level of detail, time horizons and time-steps. Models covering a spatial dimension that is greater than several or multiple buildings is generally rather simple, with highly aggregated modelling approaches employing almost constant conversion efficiencies between energy carriers [384]. Figure 3-12 shows the relationship between model spatial coverage and model complexity.

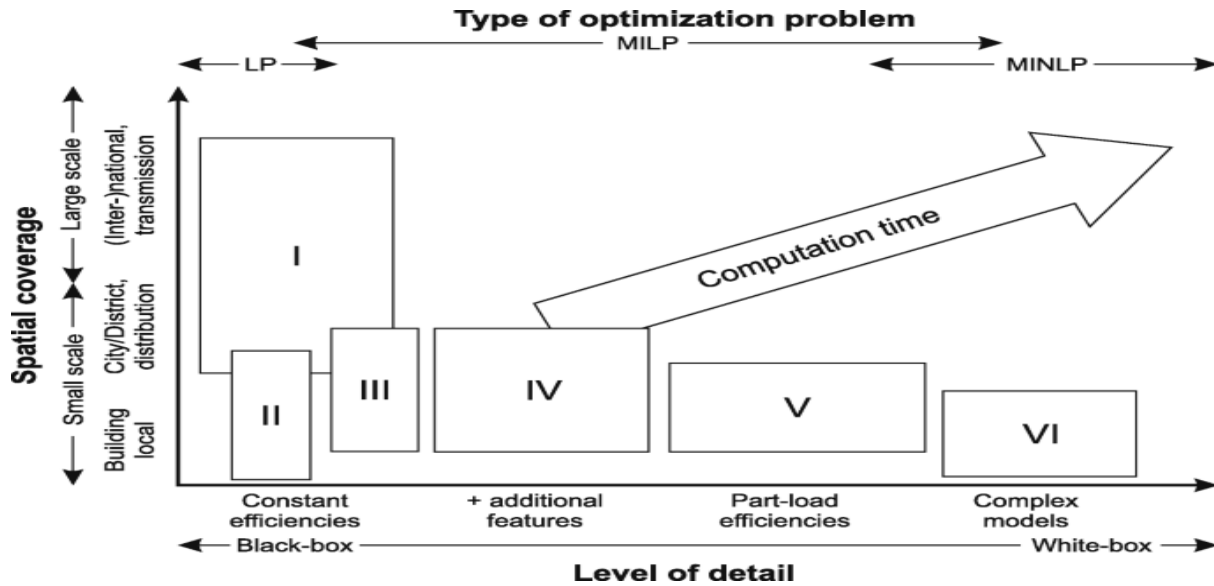


Figure 3-12: Spatial coverage, model level of detail and typical optimization problem formulation.

From Figure 3-12 is noted that that complex energy and generation planning models are needed as the spatial coverage increases. They are less complex for small scale building level.

Available MES can be Classified as follows based on their level of detail and spatial resolution.

- i.) large-scale grid studies relying on simplified models,
- ii.) simple tools for quick assessments of small-scale energy systems,
- iii.) building and city district energy system design studies with simplified models,
- iv.) on-site energy system studies with additional features,
- v.) mixed-integer linear programming with part-load efficiencies and
- vi.) mixed-integer non-linear programming with complex models.

3.25.3. Model Formulation

The common modelling approaches for bottom-up models are simulation optimization and partial-equilibrium models newer approaches include co-simulation and agent-based-modelling. Simulation is descriptive, i.e., it forecasts how the energy system might evolve, optimization is normative i.e. primary aim being to provide scenarios of how the energy system may evolve. Continuous models with linear and nonlinear behavior are obtained when

the physical world is described e.g. power generation, transmission, distribution, infrastructure and their components [384].

For a modeler to generate a mathematically tractable model for integrated simulation or optimization problems, there is need to bring equations to a common problem formulation. The mostly commonly used methods are linear programming (LP), mixed-integer linear programming (MILP), mixed integer non-linear programming (MINLP) and dynamic programming (DP). In linear programming (LP) all the relationships are expressed in fully linearized terms which make LP an easy-to-use technique with the ability to deliver quick results. But with use of constant coefficients being the main disadvantages, that lead to deviations when describing non-linear phenomena. Almost all optimization models for energy planning and technology-related, long-term energy research are LP models. The mixed integer non -linear programing (MILP) is an extension of LP that allows a greater detail in formulating technical properties and relations. The mixed integer non -linear programming (MILP) adds decision variables and non-convex relations that allow, to model an on/off mode for individual units. MINLP can also consider non-linear objective functions and constraints meaning that it most closely approximates real world systems. The challenge with this feature is that it adds a layer of complexity because the identification of the global optimum among the local optima in non-linear problems generally requires greater computational ability and effort. The MILP and MINLP models are generally applied on small scale energy systems like dispatch modelling of combined heat and power plants or thermal energy storage utilization in an energy system with high shares of distributed energy sources because due to computationally costly solution process [384].

The dynamic programming (DP) is applied to determine an optimum growth path by dividing the problem into several simple sub-problems for which an optimum solution is established and then combined to a global solution. Specific areas of application for The dynamic programming (DP) include distribution system expansion planning or the optimal operation of a distribution network having decentralized generation sets [384].

3.25.4.Data

Modelers face challenges with the vast amount of data needed for detailed bottom-up models. The reason is that the data needed is often not available because it is either not measured e.g.,

high-resolution load profiles of gas and electricity, the data is confidentially commercially, relates to the future and thus the data is highly uncertain or has doubtful quality. A few methods use probabilistic approaches, interval programming, possibilist approaches, robust programming among other to deal with this issue, but majority of energy system models apply deterministic logic e.g., MARKAL, MESSAGE, etc. and do hence they do not account any uncertainties. The probabilistic approaches apply probability density functions for the input variables [e.g., the Weibull distribution of wind speed patterns. In comparison, the possibilistic approaches, which are also called fuzzy approaches, use membership functions in description of uncertainties. The interval linear programming approach deals with uncertainties in the system constraints and the objective function, by specifying lower and upper boundaries, but they cannot handle distribution functions[384]..

3.25.5. Specific Modelling Aspects

Planning models have a long-time horizon and coarse temporal and spatial resolutions compared to the operational models which have shorter time horizon and finer temporal and spatial resolutions. Finer temporal and spatial resolutions are needed for variable and distributed resources due to inclusion of energy storage, and limited transport capacities of transmission lines. The level of detail is increased which affects mathematical tractability and computational effort required. Some particular levels of detail, spatial and temporal resolutions are needed that are different from energy vectors and the technical infrastructure in a MES[384]..

3.25.5.1. Level of Detail

Energy models have different level of detail that can be classified into black-box, grey-box, and white-box representations. The Black-box models consist of models that are highly aggregated, data-based input-output models that have no representation of the underlying physical principles leading to straightforward and easy-to-solve models. Such models used should be appropriate and accurate enough for the problem to be solved. White-box models are based on physical principles to determine load flows and conversion efficiencies and they offer higher degrees of detail. This results in increased modelling effort while mathematical tractability causes issues with the modes. The Grey-box models apply simplified physical representations, at aggregation level and degree of detail lying between a white-box model

and a black-box model. About all modelling tools used for nationwide energy forecasts e.g. MARKAL/TIMES, MESSAGE, etc. apply grey-box or black-box approaches. white box models which are complex have limited spatial coverage and very few models if any apply the approach[384].

3.25.5.2. Spatial Resolution

Energy models should consider spatial dimensions since demand and supply occurs in different locations and energy must be transferred to connect demand with supply using some energy transfer infrastructure. Houses and residential buildings are the smallest known common entities in energy modelling. MES of the next resolution size are districts or cities which are also subject of intense research. Energy studies with higher spatial coverage generally do not account for system operation and infrastructure details.

Data aggregation is necessary for modelling MES to make the problem computationally tractable and to account for unavailable or unmeasured data. Application of different spatial and temporal resolutions yield deviating results. Studies have shown that applying different spatial resolutions yield different results for the optimum heat supply strategies. In electrical network analysis, bus-aggregation methods are applied for network reductions. The simplified networks are applied in determining effects of aggregating electric loads in the[384].

3.25.5.3. Temporal Resolution

Temporal resolution is important because the use of time-aggregated data, like averaged hourly values, create deviations in the results. Design capacity of a micro combined heat and power plant tends to vary half between analysis using 5-min and 1-h time-steps. Modelling assumes that fast phenomena reach equilibrium at the end of a time-step which is quite challenging when modelling MES since they cover a wide range of time scales, from microseconds in power systems operations, hours for gas transport in transmission lines and months for seasonal influences renewable energy resources. A possible counter measure to this challenge is to interlink long-term energy system models with short term electricity system models. Although information flow from long-term models to short-term models works well, the reverse is quite challenging. The main challenge with MES modelling is selection of a proper temporal resolution fitting the scope. Selection of unsuitable resolution

can lead to over -or-under estimation of the share of renewable energy sources (RES) to be integrated. [384].

The general range of spatial resolution for energy modeling is demonstrated in Figure 3-13.

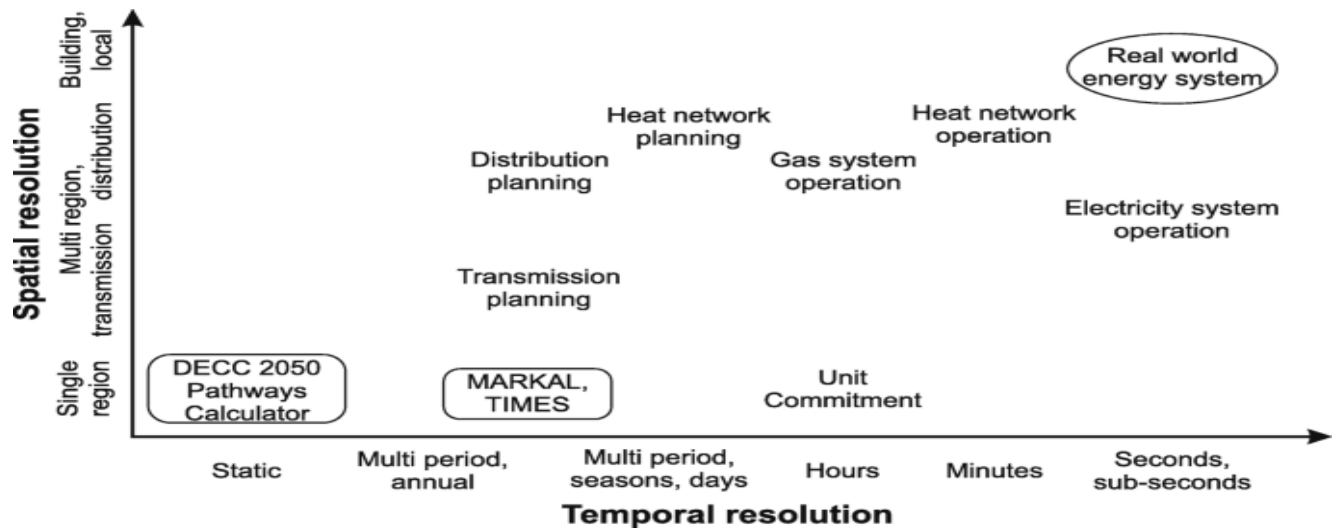


Figure 3-13: Spatial and temporal scales in MES[382].

Figure 3-13 demonstrates the different spatial and temporal scales needed for planning and operation in MES and current MES model resolutions.

3.26. Assessment Criteria

It is critical to choose the right assessment criterion and performance indicators in multi energy system modelling. The economic, environmental, and technical (energetic or exergetic) are most common. Others are sustainability, resilience, or socio-economic effects. There is both Qualitative and quantitative criteria but quantitative criteria are applicable for formulation of objective functions. The assessment and performance indicators can be generated from absolute or relative values, in a single- or multi-objective approach[384]..

3.26.1.Economic Assessment

The economic assessment is the most widely used evaluation criterion applied from planning to the operational stages with the main premise being minimization cost and or the maximization of profits. Discounted cash flow or the net present value theory are usually employed during planning. In the operational level cost and revenue analysis is typically undertaken.

3.26.2.Energetic Analysis

An Energetic Assessment compares the energy output to energy input, based on the first law efficiency or energy efficiency. Energetic assessment can be done for individual components or the whole energy systems especially during operation or over a certain period. Efficiency should always be compared to a reference case e.g., comparing energy savings by cogeneration to separate generation.

3.26.3.Exegetic Analysis

Exegetic assessment compares the first and the second law of thermodynamics. Exergy is used to describe the maximum share of energy that is capable of being converted to useful technical work. Exergy that is consumed to provide an energy service, but energy can't be created nor destroyed. Therefore, exergy is ideal for comparing different energy carriers in a multi-energy system. Exergy analysis facilitates evaluation of cascading energy usage and thus is a powerful tool for use in identifying causes, locations, and magnitudes primary energy losses.

3.26.4.Environmental Assessment

An Environmental Assessment covers the wide range of impacts of MES on the environment e.g., greenhouse gas emissions gas emissions, ground water pollution, effect on biodiversity and air pollution. The assessment can distinguish between local impacts, like NO_x-emissions, and global impacts like greenhouse gases emissions and chlorofluorocarbons [384].

3.26.5.Reliability Assessment

Reliability assessment is used to rate performance of energy systems in provision of adequate supply. The main objective of reliability assessment is to identify the weak and critical parts of the energy infrastructure, like outage rates, the failure rates of overhead lines and operational decisions. Reliability indicators predict future events with no precise estimation and so must be assessed probabilistically. Typical indicators are indicators are loss of load probability (LOLP), loss of load expectation (LOLE), expected energy not served (EENS) and loss of energy expectation (LOEE) [384].

3.27. Grid-based MES Modelling Approaches

Other than supply and demand, grid-based MES models should consider the energy flows in the networks, energy storage and conversion of energy between networks. Approaches applied

are the integrated approach and model linkage or co-simulation approach. All components like networks, converters, storage are modelled within the same framework in integrated approach while in co-simulation or model linkage, several or all components have their own dedicated model, which are then coupled by a superior tool., The sub-systems are black boxes for the coupling tool. [384].

3.27.1.Energy Network Modelling Approaches

Energy transmission via networks is modelled through various levels classified as black-box models and power flow (grey- or white-box models) models. Type I network flow models are energy models that feature energy transmission without losses. In type II network flow models, losses are captured as a function of the corresponding flow. Power flow models are the most accurate and are based on conservation of flow and on conservation laws, but additionally capture non-linearities [384].

The network models are relatively simple and the same for the most common energy networks i.e., gas, electricity, gas district heat. The power flow models are more complicated though. Load flows are determined using physical laws like voltage-current relationship, or fluid flow and hydraulic pressure etc. There is no common model for all energy carriers because the physical relations tend to be specific for different energy carriers. There are dedicated model tools for each type of network for static load flow calculation based on physical laws. Examples are PSS SINCAL, NEPLAN, or DigSILENT PowerFactory models. PSS SINCAL, and NEPLAN model district heat and gas networks, but it is not possible to interconnect each energy carrier [384].

3.27.2.Electric Networks

The two approaches to model electrical power flow, are linear DC model and the more realistic AC model. Kirchhoff's law is used to determine the active power flows in the DC model, which is dependent on maximum power capacity and power line resistance. The linear DC power flow is often used in operational electricity system models for reduction of complexity and computation of time for non-linear optimal power flow problem. Practically, DC load flow models were used for the German electricity grid where one investigated long-term grid expansion required for RES integration, while the other was applied to establish the

optimal location of storage power plants in 2020. In Turkey, the DC load flow network representation was applied in integrated day-ahead electricity market modelling [384].

Since AC load flow accounts for active and reactive power flows, there is a need for data on capacitive and inductive behavior of the transmission system lines. These extra details have the effect of increasing model complexity and hence longer computation time. It remains challenging to solve large-scale electricity systems having AC power flow representation because for some operation states, standard methods like Newton-Raphson or optimal power flow do not give any results which prevent full AC power flow models from wide scale adoption in real-time application. Many load flow calculation tools can handle AC power flow calculations. AC load flow representation can be applied to determine the optimum power flow for interconnected systems of energy hubs. AC power flow computations can also be applied in determining optimal load flow in the distribution grids [384].

3.28. Chapter Conclusions

Various sustainability indicators can be used to assess the sustainability of energy sources and power plants within the five dimensions of energy sustainability. The exercise is a multicriteria in nature and several indicators must be identified and quantified to enable assessment. And ranking.

Life cycle assessment facilitate the evaluation of a product over its entire life cycle, and across various environmental indicators. Life cycle analysis (LCA) is an effective and reliable tool in energy planning for the transition. The assessments cover impacts from extraction, processing and transportation of fuels, construction of power plants and power generation. Life-cycle assessment (LCA) of power generation technologies is very useful as the world seeks ways to meet growing electricity demand with less health and environmental impacts. However, the LCA is still an evolving methodology having some barriers and challenges but has significantly helped in improving the understanding of the lifecycle of energy technologies, their greenhouse gas emissions, related air pollutant emissions, and water-use levels and impacts in heat and power generation. The application of LCA tool facilitate the implementation of analytically thorough and environmentally holistic approach in assessment and comparison of power generation technologies. The main application of lifecycle assessment is to identify the environmental impacts of goods and services over the entire life

cycle of the product, service, or energy system. In the power sector, LCAs are used to assess the environmental impact of power generation technologies enabling power producers to make more informed decisions on environmental protection and sustainability of options available.

As a result of growing demand for energy, energy models have been identified as critical drivers in planning, designing, and implementing suitable energy technologies. Energy system models have become the main supporting tool for energy policy. Modern challenges in energy planning and management require energy systems models that integrate technical, environmental, and societal aspects of the energy systems. The design of the energy transition pathways for sustainable electricity requires modelling tools that can accommodate high penetration of renewable energy sources while considering the evolution of fossil fuel sources, the cost of technology, natural dynamics of renewable sources and inherent benefits of low carbon sources like nuclear and cleaner fossil fuel technologies and other sources of energy for power generation. There is however no single electricity model tool that addresses all sustainability and other issues related to the transition of the electricity sector and the tools selection and application is a function of specific model objectives to be fulfilled. This calls for careful selection of electricity planning and generation optimization models or a combination.

CHAPTER 4:

ENERGY SOURCES FOR THE ENERGY TRANSITION

4. Overview

In this chapter, various sources of energy for power generation and their impacts are discussed. The energy sources for power generation are the fossil fuels (coal, natural gas, and oil), nuclear energy which is a non-renewable sustainable resource. Others are renewable and biomass sources like wind, solar, hydropower, geothermal, biogas, biomethane, bagasse which is a special biomass, ocean energy sources like tidal, ocean thermal and wave energy resources and hydrogen gas. The chapter contains information published in the author's publication citation numbers[28, 58, 62, 93, 296, 386-390]. The nature of electricity demand requires power generation from different sources to meet the dynamic nature of electricity demand for example base load power should be cheap and less polluting. Various energy sources for power generation are presented with their characteristic and sustainability issues and opportunities.

4.18. Coal

Coal is a fossil fuel mined by underground or surface mining techniques then transferred by rail to power plants where it is pulverized and combusted in boiler furnaces for power generation[388, 391]. Coal is a black or brownish rock that burns coal to create energy. The classification of coal depends on how much “carbonization” it has gone through. Carbonization refers to the process through which the ancient organisms go through to become coal[251]. Peat is the lowest rank of coal having gone through the least amount of carbonization, while anthracite is the highest rank of coal found in areas that experienced giant earth movement like the formation of mountain ranges e.g., the Appalachian Mountains, in the United States. Peat is used as a fuel in parts of the world including Scotland, Ireland, and Finland.

4.18.1.Coal Mining and Processing

Coal is mined by either underground mining or surface mining. Underground mining is applied when coal is located below the surface of Earth, which can be as high as 300 meters (1,000 feet) deep, which is deeper than most of the Great Lakes. Miners apply elevators down

a mineshaft and operate heavy machinery to cut cuts the coal and bring it above ground., a process that can be can associated with the release dangerous and explosive gases which can make it `hard` for miners to breathe[251].

Surface mining applies when the coal is located close to the surface of the earth and the process starts by clearing the ground. Coal mining destroys the entire habitat during this process. Coal is mainly used in power plants for power generation and generates useful and valuable byproducts used in production of cement, plastics, roads, and many other things[251]. In the year 2021, coal accounted for over 40% of the increase in global CO₂ emissions to stand at 15.3 Gt, surpassing their previous peak by almost 200 Mt.CO₂ [161].

The rebound of coal-fired electricity powerthe Unitedin 2021 was compounded by higher prices of natural gas making the cost of operating existing coal power plants across the much cheaper than the operating costs for gas-fired power plants for the majority of 2021 which led to significant gas-to-coal switching which led to higher global CO₂ emissions from power generation by over 100 Mt, particularly in the United States (US) and Europe. Coal fired power plants in the US increased emissions by 17% in 2021 while the European Union experience a 16% growth in emissions from coal fired power plants in the year 2021 [161]. These phenomena show the effect of price changes on the use of competing energy sources.

4.18.2.Improving Coal Utility

Approaches to mitigate the environmental impact of coal include desulfurization, carbon capture, and re-use and recycling. In desulfurization, Scrubbers are installed in smokestacks to remove to remove sulphur dioxide (SO₂) emissions release to the atmosphere. In carbon capture, CO₂ is separated from coal emissions and a concentrated stream is injected underground (sequestration). Reuse involves reclaiming and using the land used for coal mining for applications like as airports, landfills, and golf courses. In coal recycling, coal wastes can be used to produce products like cement and synthetic gypsum for wallboard. [184].

4.18.3. Advantages and Disadvantages

- i. Coal is a reliable energy resource used in dispatchable power sources for use any time, any day and night, summer and winter, sunshine, or rain, to provide fuel and electricity.
- ii. Mining is one of the most dangerous jobs globally. Miners are exposed to toxic gases and dust and face the dangers of mine cave-ins and explosions.
- iii. while use of coal is polluting the environment and emits high quantities of greenhouse gases. Burning coal emits many toxic gases and pollutants into the atmosphere. Additionally, coal mining can cause the ground to cave in and create underground fires that burn for decades.

4.18.4.Sustainability of Coal

The combustion of Coal releases pollutants like oxides of Carbon, Sulphur, and nitrogen into the atmosphere, which becomes a health hazard. The composition of ground water and sea water is changed by acidic rains which makes it fatal to human and aquatic life. Particulate matter from coal-combustion induces long-term health consequences. Coal power plants may also be associated with lung cancer incidence at the national level [392].

Fine particulate matter (PM_{2.5}) can cause adverse health outcomes e.g., long-term exposure to PM_{2.5} can lead to shorter life expectancy and higher mortality risks from lung cancer and cardiovascular diseases. Improved air quality has been correlated to better health, prompting many countries to implement regulations on air pollution [392].

4.19. Geothermal Energy

The content of this section is published in journal papers [44, 58], and conference papers [206, 347, 388, 393, 394]. Geothermal energy is heating the earth's which is accessed drilling steam production wells deep below the earth's surface. Steam or hot water is mined and for power generation using a variety of technologies including direct steam, flash steam, and binary technologies for converting geothermal energy to electricity. The most common technologies applied are the flash steam and binary technologies [351]. The word geothermal is derived from the Greek word "geo" which means "earth" and "thermos" meaning [109, 226], and therefore, geothermal means the thermal energy from the earth. Geothermal energy is heat

derived from the earth's interior out of radioactive decay and is only useful if it reaches the earth's surface in sufficient quantities[395]. This heat from deep in the crust reaches the earth's surface for possible exploitation as heat and electricity by three important mechanisms and media. These are namely, ground water circulation, magma extrusion and crustal plate movement[395, 396]. A heat carrier is needed to deliver the heat in convenient and enough to the surface of the earth and is called a geothermal fluid[109, 395, 396]. As an energy resource, geothermal energy is renewable and ideal for supply of base load electricity and other direct uses sustainably while mitigating against greenhouse gas emissions from conventional energy sources like fossil fuels [397-400]. It has significant potential to supply long term, secure and reliable base load electricity and heat energy with low greenhouse gas emissions [401].

Geothermal energy development and electricity production is a thriving international market with many players at various stages of the project cycle [109, 402, 403]. The earth has been radiating heat from its center for close to 4.5 billion years. It is estimated that at about 6437.4 km (4,000 miles) in the interior of the earth's crust, the temperature is about 9932°F (5,500°C) [109]. About 42 million megawatts (MW) thermal power flows from the Earth's interior, mainly by conduction. The mantle is estimated to have a temperature of between 300 and 350°C and about 4000°C at the base of the mantle. Assuming an average surface temperature of about 15°C, the total heat content of the earth can be estimated at 12.6×10^{24} MJ while the crust has about 5.4×10^{21} MJ. This heat is huge but only a small fraction is exploitable due to several challenges and limitations [404]. Geothermal potential is considerable with the amount of heat within 10 000 meters of the surface of earth alone having equivalent energy that is 50 000 equivalents of global oil and gas resources[109, 405].

4.19.1. Thermal Gradient of the Earth

The thermal gradient of the earth on average is 2.5 to 3 °C/100 m. [398, 403, 404]. This refers to the temperature rise per unit depth as you move deep into the earth's crust from the surface [109, 406]. It is more feasible to exploit geothermal resources whose thermal gradient is above the average [407, 408], with global average of above surface temperature about 15°C [401]. At thermal gradient of 30°C/km, it implies that at a depth of 5.5 km, the temperature is about 180°C [109]. This is exploitable geothermal energy depending on availability of other enabling conditions for geothermal energy exploitation, especially the

geothermal fluid and supporting rock structure. The advantage of geothermal energy is that it is technically inexhaustible having a constant heat flow for billions of years in the past and future. Figure 4-1 shows the thermal gradient of the earth.

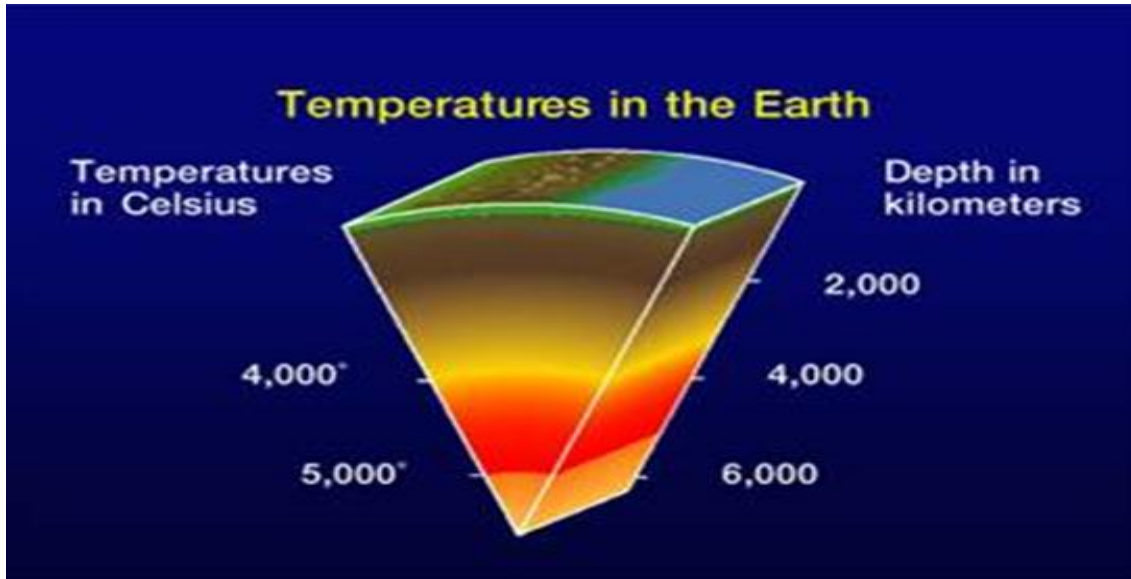


Figure 4-1: The Earth's temperature [109]

From Figure 4-1, it is noted that the earth's temperature increases as the depth increases. It reaches about 5500°C at about 6000 km deep.

A viable geothermal system consists of a heat source, a permeable rock structure and has water as a heat or energy carrier. To establish the viability of a geothermal reservoir, resource developers must drill through the earth and test the resource temperature and geothermal fluid flow rate. A thermal aquifer shown in figure 2 below is formed when rainwater or snow melts and feed the underground thermal aquifers with the water. Steam or hot water is the formed and trapped in cracks and pores embedded between a layer of impermeable rock structure, leading to the formation of a geothermal reservoir [109, 409]. To exploit this resources requires drilling of wells into the reservoir to extract the fluid and drive it to the surface for power generation in central or wellhead powerplants [410]. In some cases, there is surface manifestations of the resource in form of hot water springs, geysers, and fumaroles[109, 226]. Figure 4-2 demonstrates the positional relationship between the critical elements of a geothermal reservoir.

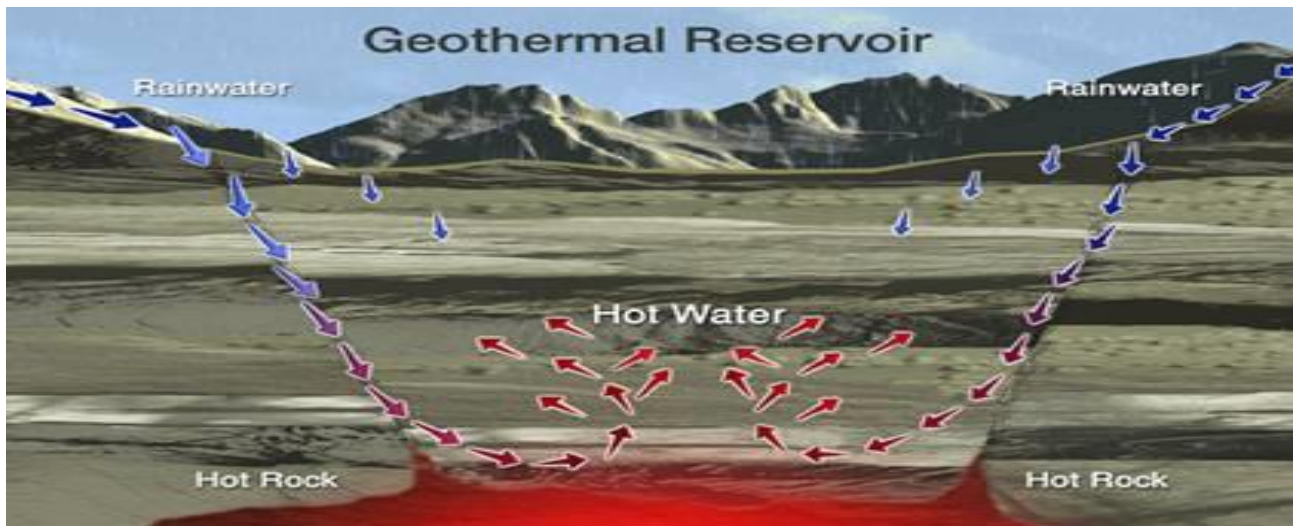


Figure 4-2: The Formation of a geothermal reservoir [109, 411]

From Figure 4-2, it is noted that a geothermal reservoir has a hot rock as heat source, water source like rainwater, and a permeable rock structure between impermeable rocks.

The global geothermal potential is significant with about 99% of the earth having temperature above $1,000^{\circ}\text{C}$, while 99% of the remaining 1% is hotter than 100°C [399], hence the possibility of having low temperature geothermal resource [412]. This implies that geothermal energy alone has the capacity to meet the entire energy needs of humanity today [413]. Geothermal power plants have average system reliability of about 95% and load factor greater than 90% making them ideal for base load power generation and application [414, 415]. Although electricity generation from geothermal energy resources is steady, continuous, and hence reliable, leading to higher electricity generation per MW of installed capacity, the global electricity generation remains low [396, 401, 414], and globally contributes less than 1% in terms of global electricity generation capacity from different sources [414, 416].

In 2014 electricity generation from geothermal was 73.3 Terawatt-hr. (TWhr.) with production in 24. This grew slightly to 75 Terawatt-hour (TWhr) in 2015 which is a mere 2.3% growth in a year accounting for 0.3% of global electricity production in 2015 [396, 414, 417]. According to [396], global geothermal electricity generation capacity by the end of 2016 was about 12.7 gigawatts (GWe). In the study by [418, 419] it was observed that in 2017, twenty four countries globally produced geothermal power with a combined installed power

generation capacity of 13,270 MWe with about 14,165 MWe under development. By end of 2019, twenty-nine countries globally had combined geothermal electricity generation capacity of 15.4 GW [417, 419, 420]. According to [421] geothermal capacity will be about 18.4 GW by 2021. The year to year geothermal electricity capacity growth between 2005 and 2020 varied between -1.09% and 5.4% growth and average growth in capacity of 4.01% [420]. The global economy was affected by the Corona virus pandemic in 2020 which realized a mere 1.35% growth in geothermal electricity capacity. This is quite low compared with the growth rates for wind and solar electricity generation.

4.19.2.Environmental Impacts of Geothermal Energy

Geothermal electricity development and exploitation has environmental impact on water, land, and in form of noise, seismic and land subsidence risks, gaseous emissions, liquid effluents, and geothermal related solid waste disposal challenges. Geothermal development has on surface and subsurface affects and structures with main elements being the drilled production and injection wells, the powerplant structure with related energy conversion systems and pipe network connecting the wells and the powerplant causing visual effect and surface obstruction to migratory paths[422]. Geothermal power plants emit carbon dioxide and particularly flash steam and those that do not employ geothermal fluid reinjection. Possible carbon dioxide emissions from geothermal plants exploiting hydrothermal resources are about 0.01 – 0.05 million metric tons (MMT) of carbon/quad of energy 10×10^{18} J. which much less compared to coal which emits about 29 MMT/quad, fossil oil emits about 21 MMT/quad; and natural gas emission is about 15 MMT/ quad. Other emissions in low levels are SO_x, NO_x, and minimal particulates. Closed loop conversion systems are assumed to have no gaseous emissions [422]. In other studies, it was established that geothermal energy is clean with low CO₂ emissions, of about 0.893 kg CO₂/MWh, compared to oil based plants which emit about 817 kg CO₂/MWh and gas based plants emit about 193 kg CO₂/MWh [423].

In the geothermal electricity project cycle, the environmental impacts begins to be severe during and after the exploratory with activities like drilling and well testing taking place among others [424]. Geothermal energy resources are often located in environmentally sensitive areas for example the Olkaria in Kenya is in the middle of a protected national park while the surrounding area is highly productive agricultural farmland with high population

density; many human settlements and related socio-economic activities [425]. It is therefore necessary to control and manage geothermal activities to ensure less or no negative impact to the neighborhood and environment [109, 411, 425]. The environmental impact caused by geothermal energy is a function of the conversion technology applied and application of geothermal with direct application having the least negative effects. Geothermal powerplants do release some amounts of sulphur dioxide, carbon dioxide and hydrogen sulphite to the environment. The powerplants emit 97% less acid rain-causing sulphur compounds, and 99% less carbon dioxide compared to fossil fuel power plants of similar size. Reinjection of geothermal fluids reduces emissions and helps in resource renewal. Hydrogen sulphide naturally exists in geothermal reservoirs and can be reduced by scrubbing [426].

Geothermal energy resource exploitation cause causes several environmental effects of like changes in land use because of exploration and geothermal power plant construction, noise pollution, visual effect, discharge of water and gases, generation of foul smell, and soil subsidence. Modern technology available today mitigates most of these effects and minimizes the impact on the physical environment [427]. The greenhouse gas emissions and global warming potential is a very important consideration when considering energy options [428]. The global concerns over high greenhouse gas emissions and global warming as well as other environmental challenges and impacts like acid rain has set in motion a global transition to a green and low carbon energy future [21, 81]. In this transition, geothermal energy has a significant role to play [429]. However, like all other energy sources, wellhead power plants and other geothermal powerplants have several negative environmental effects that should be considered and mitigated. Successful utilization of geothermal resources for electricity generation is dependent upon availability of almost zero emissions and efficient heat/steam to electricity conversion technologies [430].

4.20. Hydropower

Hydropower applies the energy in moving or flowing water to spin a hydraulic turbine which is connected to generator for electricity generation. There are two common types of hydropower, namely conventional hydropower, and run-of-river hydropower. The conventional hydropower storage by building dams to create reservoirs of water. In run-of-

river (or “hydrokinetic”) systems, water is diverted from rivers to spin hydraulic turbines [351].

Hydropower represent one of the oldest sources of energy for generation of mechanical and electrical power and was the largest source of annual U.S. renewable electricity generation up to 2019. Hydropower was used to turn paddle wheels on rivers to grind grain thousands of years ago. Hydropower was also used to power lumber and grain mills before steam power and electricity. Hydropower was first used to generate electricity at industrial scale in the US in 1880 to power 16 brush-arc lamps at the Wolverine Chair Factory in Grand Rapids, Michigan, while the first U.S. hydroelectric power plant to sell electricity was developed on the Fox River near Appleton, Wisconsin, on September 30, 1882[431].

The US alone has about 1,450 conventional and 40 pumped-storage hydropower plants in operation with the oldest operating U.S. hydropower facility being the Whiting plant in Whiting, Wisconsin, commissioned in 1891 with total generation capacity of about 4MW. Most hydro power is produced at large dams on major rivers and built before the mid-1970s by federal government agencies. The Grand Coulee hydro dam on the Columbia River in Washington State, with 6,765 MW capacity is the largest hydropower facility in the US[431].

Hydropower with reservoir has higher land requirements but remains one of the highest performing power plants among renewable sources of energy. The reservoirs can be used for secondary applications like irrigation and control of floods. Hydropower also has got high operating flexibility that can improve the reliability of electricity supply[353]. Hydropower plants are often classified into conventional and pumped storage station power plants with conventional hydropower stations accounting for the largest share of hydro power generation. The LCI input of hydropower is mainly on the account of infrastructure development where production of steel and cement accounts most of the input as well as diesel oil consumption. Since no fuel is used in operation and maintenance phase, only lubricating oil used is considered with the lifetime of the hydro power stations taken as 50, with available cases of hydro power plants that have operated for close to 100 years [162, 350].

4.20.1.Environmental Impact of Hydropower

Hydropower is largely free of several major classes of environmental impacts associated with nonrenewable energy sources. The construction of hydropower is associated with emissions

produced in plant project development and equipment manufacture. can cause the release of Greenhouse gases like methane, and carbon dioxide are released as a result of inundation and decomposition of vegetation by the reservoir with significance of impacts depending greatly the plant age, size, and geographic location of the reservoir as well as amount of vegetation and soil carbon flooded. Hydropower provides an opportunity to minimize production greenhouse gases and other pollutants compared with fossil fuel and biofuel use[39, 432].

Hydropower plants generate few solid wastes compared to other power plants. Although hydropower plants require land for waste disposal of material dredged from reservoirs or waterborne debris, very small land is needed compared with those needed for the continuing disposal of coal ash and slag. Hydro power generation does produce hazardous or radioactive wastes which require safe long-term storage facilities. Other environmental impacts associated with the overall fuel cycles are minor or nonexistent for hydroelectric power. Such externalities associated with many power plants include impacts associated with resource extraction (e.g., coal mining, oil drilling), fuel preparation (e.g., refining), and transportation (e.g., oil spills, other accidents)[186, 432].

The potential environmental impacts of hydropower include habitat alterations because large dams can inundate large areas of terrestrial and river habitats and displace people from their homes. Water diversion from the natural stream channel or curtailing reservoir can lead to drying of streamside (riparian) vegetation. Limited water releases degraded habitat for aquatic organisms. Stagnant water in reservoirs can trap waterborne sediments and nutrients leading to undesirable proliferation of algae and aquatic weeds (eutrophication), while water spilled from high dams may become supersaturated with nitrogen gas, leading to gas bubble disease in aquatic organisms inhabiting the tailwaters[39, 432]

Hydropower projects affect directly affect aquatic organisms' life like blocking the upstream movements of fish, which can have severe consequences for anadromous fish (e.g., salmon, steelhead, American shad), catadromous fish (e.g., American eels), and riverine fish which seasonally migrate to spawn (e.g., sturgeon, paddlefish). Fish can also be entrained during downstream movement (i.e., drawn into the power plant intake flow). Such Entrained fish are exposed to physical stresses like pressure changes, shear, turbulence, strike as they pass

through the turbine, leading to disorientation, physiological stress, injury, and/or mortality[432].

Although hydropower generators do not directly emit air pollutants, the dams, reservoirs, and as well as the operation and maintenance of hydroelectric generators has some environmental impacts[431]. Dam structures may obstruct fish migration and change natural water temperatures, river flow characteristics, water chemistry, and silt loads which affect the ecology and the physical characteristics of the river. Reservoirs and the operation of the dam may create forced relocation of people. The physical impacts of a dam and reservoir, dam operation, and the use of the water can induce environmental changes over a much larger area than the area a reservoir covers[431].

The manufacture of concrete and steel used for equipment manufacture produce emissions e.g., use of fossil fuels for making these materials, while the emissions from the equipment could be associated with the electricity that hydropower facilities generate. With the long operating lifetime of a hydropower plant which is 50 to 100 years, these emissions are offset by the emissions-free hydroelectricity. The actual emissions emitted from hydropower plants depends on many site and regional factors[431].

Hydropower turbines kill and injure fish that pass through the turbine. Research sponsored by the U.S. Department of Energy showed that well designed turbines can reduce fish deaths to lower than 2%, compared with fish kills of 5% to 10% for the best existing turbines. Fish species like salmon and shad swim up rivers and streams from the sea to reproduce in their spawning grounds in the beds of rivers and streams and this critical movement can be interfered with by dam construction way. The solution to this challenge include the construction of *fish ladders* and elevators which assist the fish move around or over dams to the spawning grounds upstream[431].

4.21. Petroleum /Oil

Petroleum or oil is a fossil fuel with applications in power generation in diesel power plants and transportation [252]. The petroleum supply chain includes operations like crude oil extraction and transportation, oil refining and consumption of diesel, gasoline, diesel, and other refinery products. Oil products used in power generation are heavy fuel oil, diesel, and petrol[279, 280].

4.21.1.Oil Reserves

Petroleum is a liquid fossil fuel. Which is also called oil or crude oil. Oil is trapped within the underground rock formations, but in some areas, oil bubbles right out of the ground like oil at the LaBrea Tar Pits, in Los Angeles, California, U.S., where big pools of thick oil bubble up through the ground while remains of animals that got trapped some thousands of years ago are still preserved in the tar. However, most of the world oil is still trapped deep under the ground and can only be accessed by drilling. In some areas, oil deposits are on land, and others are under the ocean floor. Many successful oil sites supply oil for about 30 years or longer 24 hours a day, 7 days a week and throughout the 365 days of the year[251].

4.21.2.Petroleum Refining and Products

Extracted oil must be refined since oil is a mixture of different hydrocarbons and contains many chemicals besides carbon, and some must be removed. About half the world's petroleum is converted into gasoline., while other products are diesel and heavy fuel oil which are used in diesel power plants as fuels While the remainder is processed and used in manufacture of various products like nail polish and rubbing alcohol, or solid products such as water pipes, shoes, crayons, roofing, vitamin capsules, and thousands of other items.[251].

4.21.3.Advantages of Oil

- i. Oil drilling is relatively inexpensive and is more reliable and dependable source of energy and money for the local community.
- ii. Oil is a portable energy resource with wide applications in mobility and power generation, while petroleum is also an ingredient in many products.

4.21.4.Disadvantages of Oil

- i. Burning oil in the form of diesel, gasoline and heavy fuel oil pollutes the environment. It releases hazardous gases and fumes into the atmosphere.

- ii. Oil is more expensive than natural gas and coal making it less competitive. It contributes to the high cost of power in countries that rely on diesel power generation.
- iii. Oil spills and leakages are a possibility while oil can explode out of the well and spill into the ocean or surrounding land. Oil spills cause environmental disasters, since oil floats on water and make it look like food to fish and ruin birds' feathers[251].

4.22. Natural gas

The content of this section is contained in publications[96, 279] co-authored by the supervisor Prof. Oludolapo. Natural gas is used as a fuel in gas engines, gas turbine and diesel engines as pure gas or dual fuel plants. Natural gas is an attractive option from environmental perspective as it is having relatively low carbon emission[252]. Natural gas is a naturally occurring cleaner fossil fuel compared to other fossil fuels like oil and coal. Natural gas is cheaper and widely available globally and with possibility of substitution with biomethane which is regarded as renewable natural gas. The main elements or constituents of natural gas are methane (CH_4), nitrogen, ethane, propane, helium, hydrogen sulphide water vapor, and carbon oxide and water vapor. The energy content is influenced by the composition of methane, while hydrogen sulphide is destructive to the engine parts. The various design modes of natural gas-powered engines are spark-ignition engines, pure gas engines, dual fuel, and bi-fuel engines. Natural gas is an attractive engine fuel mainly because of environmental friendliness, easy substitution with petrol in spark ignition engines due to high octane rating, low operation and maintenance costs, and low price and high combustion efficiency compared to other fossil fuel[280]

Natural gas is a flammable gas, mainly made of methane and other hydrocarbons, that occur naturally underground and used as fuel[184]. Natural gas is a fossil fuel trapped underground in huge reservoirs and usually measured in millions, billions, or trillions of cubic meters due to the huge quantities[251]. In the year 2021, emissions from natural rebounded well above 2019 levels to 7.5 Gt, due to demand increase in all sectors. Natural gas is a hydrocarbon, and which produces CO_2 on combustion and can be used as a cleaner substitute of coal and diesel

oil in gas turbines. Natural gas accounts for close to 22% of the total, global electricity generation compared to about 40% for coal[433]. Natural emits 50-60% less CO₂, no SO₂ and negligible particulate emissions compared to coal [12]. However, natural gas is mainly methane CH₄, which is a greenhouse gas, and natural leakages can have a significant impact on the climate change.

Natural gas is a cleaner burning and more flexible alternative to other fossil fuels today. Natural gas has a wide source of applications in residential, commercial, industrial, and transportation sectors and power generation. Although natural gas is a cleaner fossil fuel, it emits greenhouse gasses (GHG) mainly methane which is 8 to 87 times as potent as CO₂[30]. Although there are significant opportunities reduce the GHG emissions that are associated with gas extraction, delivery, and power generation in power plants. [351]. Natural gas is mostly transported by pipelines can be transported and stored as liquefied natural gas (LNG) which is 1/600th the volume of its gaseous for easy transport by LNG ocean tankers. The process requires liquefaction and regasification facilities at loading and export terminals as well as import terminals [351]. Natural gas can also be stored and transported as compressed natural gas (CNG). For easy handling, transport, and use.

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4.22.1.Mining Natural Gas

Natural gas is found in reserves located a few hundred meters underground, and can be reached by drilling straight down., but the gas does not form I big pockets form in big open

pockets, but instead is trapped in rock formations which can stretch for kilometers. Natural gas can be reached by a process called “hydraulic fracturing,” or fracking. Which uses high-pressure water to split the rocks apart underground to release the natural gas trapped in rock formations. An acid can be used to dissolve the rock if it is too hard or use tiny grains of glass or sand to prop open the rock for the gas to escape.

4.22.2.Applications of Natural Gas

Natural gas can be used for heating and cooking as well as power generation [251]. Natural gas can also be turned into a liquid form, as liquid natural gas (LNG). LNG is a cleaner energy resource than other fossil fuels. LNG is easier to store and can be used for applications like replacement for gasoline[251]. Natural gas is an important source of energy for power generation because it is cheaper, reliable, and produces less emissions. Natural gas acts as an important backstop for variable renewable i.e., wind and solar contributing about one third of US electricity. Natural gas emerged as a leading choice in power generation in the powerplants in 1990s because of concerns over the environment impact, cost and technological advances made in cleaner fuel as opposed to coal, and diesel power plants[434] Other than power generation, natural gas has applications in transport, domestic, residential, industrial and commercial thermal application [434]. In the year 2020, natural gas accounted for about 38% of total U.S. consumption accounting for 33% of the U.S. electric power sector's energy consumption[435].

4.22.3.Steps in Power Generation Using Natural Gas.

4.22.3.1. Step 1: Extraction, Processing, and Delivery

The first step in the exploitation of Natural gas for power generation is extraction from the is extracted from Earth’s surface followed by processing and delivery to power plants by means of gas pipelines[434].

4.22.3.2. Step 2: Conversion

At power plants, natural gas is converted to thermal energy or heat which is converted to mechanical power in gas or steam turbines, internal combustion engines (petrol or diesel or

gas engines). The power plants therefore based on technology will convert energy in gas to steam in boilers or flue gases in gas turbine or direct conversion as in internal combustion engines. Natural gas can also be used in direct chemical conversion to electricity in fuel cell. The power plants either use a boiler to create steam, which generates [434]

4.22.3.3. Step 3: Power Transmission and Distribution

The various prime movers generate power by turning electric generators except in fuel cells where we have direct conversion to electricity. The electricity generated is used locally at stations or is supplied to utilities who send the power through transmission and distribution networks to consumers widely spread[435].

4.22.4. Conversion Technologies

4.22.4.1. Steam Turbine Generation Units

This is the most basic natural gas-fired electric generation consisting of a steam generation unit, where natural gas is burned in a boiler to heat water and produce steam that then turns a steam turbine to generate electricity. These basic steam generation units have fairly low energy efficiency generally between 33 and 35% of the thermal energy being converted to power[434].

4.22.4.2. Open Cycle Gas Turbine

An open cycle gas turbine power plant has a gas turbine exhausting flue gas to the atmosphere, a combustor, and the generator. It is less efficient with efficiency range of 30 -40%[101, 299]. The rotating turbine rotor shaft is coupled to a generator on one side and an air compressor on the other end for compression of combustion air. The gases leaving an open cycle gas turbine have significant quantities of waste heat which can be recovered to preheat the combustion gases, the fuel or both before admission to the combustor to improve the combustion efficiency. In larger units, the exhaust gases can be used to operate a Rankine cycle steam turbine for extra power generation by generating steam using a waste heat recovery boiler[101]. A microturbine and turbine can be equipped with an air heater (heat exchanger) through which compressed air is preheated on its way to the combustor where it meets biogas

fuel supplied via a gas supply system which can also be equipped with a preheating system [331].

4.22.4.3. Combine Cycle Gas Turbine Power Plants.

Combined cycle power plants use natural gas as fuel to run the gas turbine with exhaust heat being recovered for use to generate steam to run a secondary steam turbine working on the Rankine cycle[434]. These systems are more efficient generating more power per fuel consumed and with less environmental impact. Therefore, the main elements of the combined cycle power plant will be natural gas fuel supply system, a gas Brayton cycle gas turbine, exhaust gas heat recovery boiler, a steam turbine, and an electric generator[101, 299].

4.22.4.4. Co-generation

There are various pathways or technologies for exploitation of natural gas energy for both heat and electricity generation [386, 387, 436, 437]. Co-generation refers to simultaneous production of both electricity and heat from biogas fuel, which is also called combined heat and power. Natural gas can be used in combined heat and power, also called cogeneration for production of electricity and heat with or without upgrading[107, 438, 439]. In a typical biogas-based CHP technology both heat, and electricity plant (BHPP) can be used whereby a combustion engine is used for electricity generation. The produced electricity can be sold to the grid as well as meeting local demand. The heat produced by the combustion engine is used for many feasible applications such as in district heating and can be fed to the hot water system[440, 441].

4.22.4.5. Microturbines

Microturbines are relatively small power plants compared to the conventional gas turbines and generally have capacity of 25 to 500 kilowatts (kW) of electricity. Microturbines are ideal for residential or small-scale commercial applications. Their advantages include being very compact size, fewer and smaller moving parts, lighter in weight, cheaper and increased efficiency[434]. Microturbines are small gas turbines, generally with capacity of 25-30 kW to 350 kW. The working principle of a microturbine is like the gas turbine. The main components of micro and turbines are the combustor, compressor, and the turbine. Hot

products of combustion, enter through the turbine nozzles, and expand through the turbine causing conversion of thermal energy to kinetic energy.

In the operation of a microturbine air is taken in by induction force of the compressor for compression to desired pressure range. In more advanced cycles, the compressed air from the compressor can be directed to a recuperator for preheating by waste heat in exhaust gases before it goes to the combustor. The compressed heated air is supplied to the combustor and mixes with biogas fuel for combustion. In the combustor, the biogas fuel-air mixture burns to produce high temperature flue gases. The flue gases are directed to a gas turbine where it expands through the stages to perform work that rotates the turbine which is coupled to an electric generator for power generation[101].

4.22.4.6. Internal Combustion Engines

Natural gas can be employed as a fuel for both petrol and diesel engines with little, major or no modification based on the percentage of natural gas in the fuel intake. We also have dedicated natural gas engines in the market which run on 100% natural gas[434]. Biogas to electricity is a feasible process with different engines being optional prime movers for the electric generator. Both diesel and gasoline (Otto cycle) engines can be used as biogas fuelled prime movers for electricity generation. Dual fuel engine options with fuels like diesel and petrol are common in variable substitution ratios. The efficiency of electricity generation is a function of the prime mover and fuel combustion characteristics. Internal combustion engines have lower cost per unit power generation compared to other viable options like gas turbines and microturbines, and although factors can make alternative options favourable too in power generation like fuel flexibility and ease of operation and maintenance [442].

4.22.4.7. Fuel Cells

Fuel cells work like rechargeable batteries except that fuel is used instead of an electric recharger hence have advantage of continuous operation as compared to rechargeable batteries[434]. Fuel cells convert chemical energy of in fuel efficiently to electricity without combustion, with low emissions compared to conventional equipment/techniques. It is therefore a fuel cell defined as an electrical chemical device that directly convert chemical energy to electricity. The three main parts of a fuel cell assemble are the anode, cathode, and

electrolyte. A catalyst oxidizes fuel with ions travelling via the electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit[443]. Fuel cells development partially focuses on optimization of catalytic the layer of the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance [444]. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available. The theoretical thermodynamic efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60% [444].

4.22.5. Advantages and Disadvantages of Natural Gas

4.22.5.1. Advantages

- i. Natural gas is considered as the cleanest fossil fuel due to low levels emissions of CO₂, CO, nitrogen oxides, and SO₂ than other fossil fuels.
- ii. Natural gas is relatively inexpensive to extract and is a “cleaner” fossil fuel than oil or coal. When natural gas is burned, it only releases carbon dioxide and water vapor (which are the exact same gases that we breathe out when we exhale!) This is healthier than burning coal.

4.22.5.2. Disadvantages

- i.) The extracting and use of natural gas can cause environmental problems challenges e.g., rock. fracturing can cause mini earthquakes when high-pressure water and chemicals are forced underground.
- ii.) The chemicals used in mining natural gas can contaminate underground water sources, used for drinking or bathing.

4.22.6. Composition of Natural Gas

Natural gas is a naturally occurring mixture of hydrocarbons often found in petroleum and coal fields and as a hydrate on the seabed. It is formed by composition of organic matters[445]. Liquid natural gas is formed by cooling natural gas to a temperature of -162°C at atmospheric pressure[446]. Natural gas is mainly made of methane (CH₄) and smaller amounts of hydrogen sulfide, ethane, nitrogen propane, helium, carbon oxide (CO₂) and

moisture or water vapor. The main constituent is methane (CH₄) which is normally about 90% [447]. A natural gas engine is a mechanical engine that uses natural gas as a fuel to produce power (mechanical or electrical). There are three natural gas engine modes based on fuel namely: Spark-ignition reciprocating internal combustion engine, Gas-fired turbines, and Dual fuel gas engines [81].

The main characteristics which make natural gas attractive as a fuel for power generation and other engine application include affordability, wide availability, environmental friendliness, compatibility with the conventional spark ignition and compression ignition engine and low operational cost compared to other fossil fuels [448].

Compressed natural gas (CNG) has the following typical properties which may be slightly different from the uncompressed natural gas. These properties are summarized in Table 4-1.

Table 4-1: Typical composition of compressed natural gas in Vol% [449].

	Element	Symbol/Formulae	Volumetric %
1	Methane	CH ₄	94.42
2	Ethane	C ₂ H ₆	2.27
3	Propane	C ₃ H ₈	0.03
4	Butane	C ₄ H ₁₀	0.25
5	Nitrogen	N ₂	0.44
6	Carbon dioxide	CO ₂	0.57
7	Others	-	2.00
	Total		100%

From Table 4-1, it is noted that compressed natural gas (CNG) as a fuel is a mixture of several organic gases with the highest component being methane. Other common constituents of CNG are ethane, butane, propane, Nitrogen, and carbon dioxide.

4.22.7.Environmental Impact of Natural Gas

Natural gas is commonly regarded as the as the world’s cleanest. Combustion of natural gas produces mostly CO₂, water vapor, and some nitrogen oxides as emissions. On life basis , natural gas 490 grams of CO₂ equivalent per kWh, which is the lowest among the fossil fuels but the third-highest amount out of all of the fuel types[184].

4.23. Wind Energy

The global installed capacity of wind generation was 622 GW in 2019, with onshore wind being the second largest source of renewable electricity after hydropower with installed capacity of about 594 GW, while offshore wind generation had installed capacity of 28 GW of the installed generation capacity globally[450]. Whereas the thermal power plants like biomass, geothermal, nuclear and coal power stations, add some heat and direct emissions to the environment, wind turbines can alter both horizontal and vertical atmospheric air circulation as the notable environmental impact which may alter local temperatures, although this is negligible compared to the larger temperature change caused greenhouse gases[451, 452]. Direct climate impacts of wind power are instant but benefits of reduced emissions take time to accumulate[451].

Wind energy is used in wind power generation and other mechanical applications like water pumping. Wind can drive a wind turbine generator to produce grid connected electricity or some can be stored in a battery system [433]. The most common technology used for utility-scale wind power is a three-blade rotor mounted on a shaft that is horizontally oriented. Which is connected to a gearbox or direct-drive system for rotating an electric generator. The facilities for wind power, are called “wind farms,” and they have multiple wind turbines and transformers as well as other electrical equipment that allow power transmission grid.

The power in wind, that impinges on the blades of a wind-turbine can be established, by the formulae

$$P=CA \rho V^3/2$$

where :

C = A coefficient related to the machine design and characteristics

A = Swept area of the turbine rotor blades

ρ = Air density of the air

V = Velocity of wind

The equation shows that the power in wind is directly proportional to the blades swept area. The area, A , is proportional to the square of the diameter circular area that is swept through by the blades. It is for this reason that the generators are mounted on tall steel masts, to allow installation of the long blades generally 20 to 30 m above the ground. Examples are, the generators at the Sere Wind Farm in the north-western Cape which have blades of length 53 m in length, and a swept diameter of 108 m[433]. The height at which generators are mounted varies based on the terrain but may vary between 78.5 m and 115.0 m with ability to generate 2.3 MW at maximum speed for the 46 units installed at the station of installed capacity 105 MW. Since individual generators interact with adjacent units, a spacing of 6– 10 times the rotor diameter is commonly adopted., but for optimum use of the wind energy, some large wind farms employ apply up to 15 times the rotor diameter[433]

4.23.1.Wind Farms

The global installed capacity of wind generation was 622 GW in 2019, with onshore wind being the second largest source of renewable electricity after hydropower with installed capacity of about 594 GW, while offshore wind generation had installed capacity of 28 GW of the installed generation capacity globally[450].

An efficient, consistent wind power generation requires that wind farm be located at the right location. Long blades that are sufficiently spaced from others are needed to minimise interaction between adjacent turbines mounted on high masts. These requirements show that a large farm area is needed for maximum power generation. One or more substations are strategically located to receive the power from groups of individual wind power generators and for stepping up the voltage before feeding to the grid. The wind farm the Sere Wind Farm in the North-western Cape covers an area of 3 700 Ha from which 331 GWh (0.14% of total) of for 2017/2018 financial year for Eskom[433].

4.23.2.Advantages of Wind Power

- i. Wind power generation has no greenhouse gas emissions.
- ii. The generation does not deplete and natural resources.
- iii. Most materials related to wind generation are recyclable waste.
- iv. Several economic activities can be conducted on the land occupied by a wind farm.

4.23.3.Disadvantages of Wind Generation

- i. Power is only generated when the wind blows therefore the network it supplies should be large and flexible enough with sufficient reserve generation capacity to compensate for output variations in wind generation. Large grid capacity like Eskom generally has little problem if the share of wind is low when compared with the system capacity. Storage is required to smooth-out the variations in wind generation which adds to cost.
- ii. Wind turbines operation is associated with acoustic noise which may be disturb people living in the neighbourhood of a wind farm with experience indicating that at about 300 m or more distant from the nearest wind turbine, ambient noise levels can be as high 43 dB, which is comparable to living in a quiet suburb[433].
- iii. Wind turbines are associated with unfortunate incidents where birds are injured or even killed by the blade. However, studies show that fossil fuel energy from is about 35 times more dangerous to birds, on a GWh basis, compared with wind or nuclear plants.

4.24. Solar Energy

The sun provides light and heat at levels that are an inexhaustible as long as the solar system remains intact. The main challenge facing solar is to tap into this energy and convert it into useful forms[433]. Two technologies used in solar energy exploitation are.

- i. The photovoltaic (PV) cell, which converts solar radiation to direct current electricity.
- ii. Concentrated solar thermal energy, used to convert solar energy to steam to drive a steam turbine which turn a generator to produce electricity.

Solar thermal power harnesses energy from the sun using solar collectors whose role is to concentrate sunlight on a fluid for hot water and generation for use in steam-driven electricity generation system. Photovoltaic panels can also be applied for direct conversion of Sunlight to electricity, wherein photons increase the energy level of electrons and create an electric current. In utility-scale power generation, solar thermal power plants are more favourable than photovoltaic systems [351].

Solar Photovoltaic power is sustainable in many dimensions i.e., economic, environmental social and commercially available and reliable technically. Most commercial CSP plants work with parabolic trough technology. In this technology, direct incident solar radiation is concentrated by means of curved mirrors to heat a synthetic heat transfer fluid (HTF) running across the focal point of the solar collectors. The heated fluid leaves the solar field at about 390 °C and flows to a multiple stage heat exchanger for generation of superheated steam used to drive a Rankine cycle steam turbine. To improve stability, improve plant capacity and efficiency, most CSP plants use backup systems which may use Thermal Energy Storage (TES) systems and/or by hybridizing with other fuels can be used to supplement solar radiation [453]. For a typical 50 MWe CSP power plant, the life cycle cost (LCC) analysis yielded total internal costs of 82.8 €/MW h and total revenues from electricity of 85.7 €/MW h, with net present value (NPV) of 2.95 €/MW h. Most expenses in a CSP plant are associated with E&M and the C of the system at 48% and 20% of the expenses respectively most of it with respect to purchase of plant components and engineering and management costs[453]. The average power density of solar is about 10 times higher than wind power, but may also be lower than estimates as shown by many studies [451, 452].

Learning effects in concentrating solar power (CSP) technology has for long time been inhibited by low deployment of CSP power plants. Mainly due to consequences of a financial and regulatory stagnation in areas with direct normal irradiance availability and fast reduction in the cost of solar photovoltaic technology which is the alternative. [454].

4.24.1. Levelized Cost of Solar

The predicted LCOE will be lower than 0.10\$/kWh, but low learning rates of about 10% inferred from literature of learning rates above, will lead to about 2% contribution to globally power generation with projected LCOE of 0.06\$/kWh in 2050 compared to LCOE of

0.216\$/kWh in 2018. High LCOE values may lead to delayed deployment of CSP in the coming decades but with integrated thermal storage, the system value can be enhanced although the LCOE of PV with battery systems may be lower than the LCOE for CSP with storage from 2030 onward which may delay deployment of CSP[454].

The levelized cost for Photovoltaic is the total energy produced by PV system less storage losses computed on the basis of the capacity of the battery storage, assumed number of cycles and the storage battery efficiency. The values capture the differences in PV costs, battery costs (500 to 1200 EUR/kWh) and varying solar irradiation. Large rooftop PV systems equipped with battery storage cost between 600 and 1000 EUR/kWh while ground-mounted PV equipped with battery storage systems, have investment costs for battery storage cost of 500 to 700 EUR/kWh[354-356, 358]. Smaller photovoltaic systems are normally standardized products hence cheaper than larger battery systems which are often individualized or unique projects leading which incur extra costs of project development, high cost of infrastructure, and higher project management., although the investment costs are lower for the larger sizes, due to more economies of scale and use of more competitive pressure [356].Table 4-2 shows the levelized cost of different solar systems.

Table 4-2: Levelized Cost of Energy for PV system [354-356, 358]

	Technology	LCOE For 2021(€/Mwh)	Rank (From Cheapest)
1	PV rooftop (small, battery 1:1)	140.5	3
2	PV rooftop (large, battery 2:1)	104.9	2
3	PV ground (utility, battery 3:2)	75.8	1

From Table 4-2, it is noted that photovoltaic for grid scale application has the lowest levelized cost of energy (LCOE) while the rooftop small photovoltaic has the highest levelized cost of energy (LCOE) among the PV power systems.

4.25. Nuclear Energy

The nuclear supply chain involves a series of material processing and waste management measures with the main activity taking place in nuclear power plants where atoms split into subatomic particles and smaller atoms with release of energy through nuclear fission nuclear fission. Most nuclear power plants use uranium fuel with high concentrations of uranium (U)-235 isotopes. Heat produced in nuclear fission is used to generate steam for power generation in Rankine cycle steam turbines[351].

Nuclear energy as a nonrenewable energy source. Nuclear energy itself is a renewable energy source, but the material used is not renewable. Nuclear energy is released through nuclear fission, in which the nucleus of an atom splits into two or more particles with release of binding energy [251]. Uranium is the energy material used in most nuclear power plants Uranium is found in rocks all over the world, but nuclear power plants use a uranium, U-235 which is relatively a rare nonrenewable resource[251].

Nuclear power plants are clean since they do not pollute the air or emit greenhouse gases. And can be built in rural or urban areas, and do not destroy the environment around them. The challenge with nuclear r power plants is the complexity of plants in terms of building and operations, hence they require rare skills from scientists and engineers to develop a safe and reliable nuclear energy program. Radioactive waste produced by nuclear power plants can be extremely toxic, and can cause other impacts like causing burns, ca cause cancer, blood diseases, and bone decay among people who are exposed to it[251]

Nuclear energy is a clean energy source with carbon emissions taking place only during mining for uranium, and power plant development. The main concern with nuclear energy remains how to handle radioactive waste. The fuel reactor is the highest source of radioactive waste in the form of spent reactor fuel. The US and many other countries do not have a place for permanent nuclear waste disposal [455].

Nuclear power development requires public support to increase its share in global energy production due to negative public opinion due to a complicated past arising from multiple nuclear power plant accidents or meltdowns making it to be considered as a risky energy option. Current decarbonization commitment has generated fresh interest in nuclear energy as a clean energy resource [455].

Nuclear energy has for a long time been considered as being harmful to the environment. However with concerns over the global climate change and greenhouse gas emission, the nuclear industry has become reputable as a green power source with capacity to produce huge amounts of energy with less carbon emission[456]. Nuclear energy is currently a mature low-GHG emission energy resource that is ideal for use as baseload power. However, the share in global electricity generation has been declining globally but its share of global electricity generation has been declining since the year 1993 as a result of various barriers and risks[457].

The life cycle GHG emissions from nuclear power are less than traditional fossil sources but assumptions and conditions under which they are deployed can have serious impact on the magnitude of life cycle GHG emissions compared to renewable technologies. The published median, interquartile range (IQR), and range for LWR life cycle GHG emission are 13, 23, and 220 grams of carbon dioxide equivalent per kilowatt-hour (g CO₂-eq/kWh), respectively. Upon application of harmonizing methods to use consistent gross system boundaries and values, important system parameters yielded 12, 17, and 110 g CO₂-eq/kWh, respectively. Based on ongoing improvements, median life cycle GHG emissions could be 9 to 110 g CO₂-eq/kWh by 2050[458].

Nuclear energy is a cleaner nonrenewable energy with huge resource availability in the form of Uranium. A report dated June 2022, by Electricité de France released detailed Life-cycle assessment study based on norm ISO 14040 showed that in 2019 French nuclear infrastructure produces less than 4 gCO₂eq/kWh.

Generally nuclear power is cost competitive compared to other power generation sources except in cases with direct access to cheaper fuels. The fuel costs for nuclear plants are a small fraction of the power costs, but capital costs are greater than most coal-fired power plants and much greater natural gas power plants. However, the system costs for nuclear, coal and gas power plants are significantly lower than variable renewables[21]. A nuclear power plant project is typically a large infrastructure project globally with tendency to underestimate the costs and delivery challenges. To assess the economics of nuclear power generation the cost of decommissioning and waste disposal costs should be accounted for since they are significant[29]. Nuclear power plants require a lot of cooling hence almost all nuclear power

plants are in coastal areas or near large water bodies for easy access to large quantities of cooling water. The lifetime of the nuclear power plant is assumed to be 40 years[350].

4.25.1.Fission Energy

In a nuclear reaction, two or more nuclei or subatomic particles are involved in a collision that produces one or more nuclides. In nuclear fission is the reaction involves a heavy atom nucleus splitting into lighter nuclei with release of energy. An immense amount of energy by fission of uranium atom $^{235}_{92}\text{U}$ which is a rare uranium isotope, having a nucleus of 92 protons and 143 neutrons. Natural Uranium is dominated by a stable isotope $^{238}_{92}\text{U}$ which consists of 99.28% by mass, which is an isotope having a nucleus with 92 protons and 146 neutrons. The $^{235}_{92}\text{U}$ comprises only 0.71% of the mass of the naturally occurring uranium[433].

4.25.2.Nuclear Fusion

In nuclear fusion two or more atomic nuclei come close enough for long enough for the fuse them into heavier nuclei. The nuclei heavier than iron-56 are endothermic and for nuclei lighter than iron-56 the reaction is exothermic, hence nuclei heavier than iron-56 often break apart, while those smaller than iron-56 can fuse together. Upon fusion, some of the mass of the original nuclei is lost and transformed to the kinetic energy and some particles. Most studies involving controlled thermonuclear fusion focus on fusion of lighter hydrogen nuclei into a heavier helium nucleus, with the most energetically favourable reactants for fusion process being the two hydrogen isotopes, deuterium, and tritium. Fusion energy is the most common form of energy in the Universe since it is through thermonuclear fusion that our Sun and other stars generate energy. The main limitation for fusion energy on earth is the control of nuclear fusion [459].

Successful fusion reaction requires kinetic energy for nuclei to overcome the so-called 'Coulomb barrier' since the strong force acts only over a short distance, while the repulsive electrostatic force covers longer distances. The control of nuclear fusion requires the confinement of hot and dense plasma. The plasmas are electrically conductive, hence are magnetically controllable, with magnetically confined fusion taking advantage of this

characteristic. In inertia confinement fusion which is another approach, nuclear fusion reactions are initiated by heating and compressing a fuel target by use of laser beams[459].

4.25.3.Nuclear Fuel Cycle

Uranium is a radioactive metal found all-over the world and is the main fuel for nuclear power generation. Uranium has two main isotopes: uranium-238 and uranium-235 with Uranium-238 being the most abundant in the world but cannot produce a fission chain reaction. On the other hand , Uranium-235 is used to produce energy by fission but constitutes less than 1 per cent of the world's uranium[300].

To increase the chance of fission, the concentration of U-235 must be increased through uranium enrichment process before it can be used effectively as nuclear fuel in power plants for between three to five years, though still radioactive it is disposed of following stringent guidelines to protect people and the environment. This used or spent fuel, can also be recycled into other types of fuel for use as new fuel in special nuclear power plants[300].

4.25.4.Nuclear Waste

Radioactive waste makes up a small portion of all waste. It is the by-product of millions of medical procedures each year, industrial and agricultural applications that use radiation and nuclear reactors that generate around 11 % of global electricity. This animation explains how radioactive waste is managed to protect people and the environment from radiation now and in the future. The operation of nuclear power plants produces waste with varying levels of radioactivity. These are managed differently depending on their level of radioactivity and purpose. See the animation below to learn more about this topic[300]

4.26. Ocean Thermal Energy Conversion (OTEC)

The OTEC system can operate with a very high capacity factor and hence it is ideal for baseload applications. The cold water masses which are denser that is formed by ocean surface water interaction with cold atmosphere in areas like the North Atlantic and the Southern Ocean, sink into the deep sea basins spreading in entire deep ocean by the thermohaline circulation. The upwelling of cold water from the deep ocean is replenished by the cold downwelling of cold surface sea water[288].

OTEC is one of the continuously available renewable energy resources that could contribute to base-load power supply. OTEC resource is much larger than the other marine energy with potential of producing Up to 10,000 TWh/yr of power without affecting the ocean's thermal structure.

OTEC systems can be closed-cycle or open-cycle., with Closed-cycle OTEC applying working fluids regarded as refrigerants like ammonia or R-134a. The refrigerants used have low boiling points hence suitable for powering the generator for power generation. The Rankine cycle is the most used heat cycle for OTEC to date and is applied using a low-pressure turbine. The Open-cycle OTEC cycles apply vapor from the seawater itself as the working fluid and can supply cold water as a by-product. The open cycle OTEC system can be used for air conditioning and refrigeration while the nutrient-rich deep ocean water can feed biological technologies. Fresh water can also be produced as a by-product by distillation from the sea[460].

The ocean thermal energy conversion (OTEC) theory was first developed in the 1880s while a bench size demonstration model was developed in 1926. In 1881, Jacques Arsene d'Arsonval, a French physicist, proposed the use of thermal energy of the ocean in 188, while his student, Georges Claude, developed the first OTEC plant which generated 22 kW using a low-pressure turbine, in Matanzas, Cuba in 1930, although it was later destroyed by a storm. Claude constructed a plant aboard a 10,000-ton cargo vessel which moored off the coast of Brazil in 1935, but the weather and waves destroyed it before it could produce any power. In the year 1956, French scientists designed a 3 MW plant for Abidjan, Ivory Coast, but the plant was never completed, due to new finds of large amounts of cheap petroleum which rendered it uneconomical. It is in 1962 that J. Hilbert Anderson and James H. Anderson patented their new "closed cycle" design as an improvement upon the original closed-cycle Rankine system, as a plant that would produce power at lower cost than oil or coal. There was limited interest in the OTEC research since coal and nuclear were considered the future of energy. These cases demonstrate the early attempts to develop OTEC as a power generation system[288].

There was an uptick in OTEC research in 1970s in the post 1973 Arab Israeli War, which caused oil prices to triple. The U.S. federal government committed \$260 million into OTEC research when President Carter signed a law that committed the US to generate 10,000 MW of

electricity from OTEC systems by 1999. In 1970 the Tokyo Electric Power Company developed and deployed a 100 kW closed-cycle OTEC plant on the island of Nauru. in Japan. This power plant became operational on 14 October 1981, and generated 120 kW of electricity; of which 90 kW was used to power the plant and the remainder was used to power a school and other place. In 1981 a Russian engineer, Prof. Alexander Kalina, applied a mixture of ammonia and water to produce electricity. The ammonia-water mixture significantly increased the efficiency of the power cycle. In 1994 Saga University developed a 4.5 kW plant to test a newly invented Uehara cycle, named after its inventor Haruo Uehara. The cycle which incorporated an absorption and extraction process improved the Kalina cycle by 1–2%.[288]

4.26.1.Environmental Impact

The ocean thermal energy conversion systems have impacts on organisms inhabiting or moving through the area, but to an unknown degree. Potential biological impacts include nutrient redistribution, entrainment and impingement, organism attraction or avoidance, and biocide release, etc.[304]. The OTEC system is likely to attract fish and seabirds, while noise may interfere with animal communication, while chemicals like lubricants or anti-biofouling chemicals contaminate the ocean. The redistribution of millions of cubic meters of water per day may change the stratification, salinity, oxygen, and nutrient levels near the site which has a negative impact on organisms whose behavior is based on certain temperature or salinity gradients, while others may be affected by increased nutrient levels. Plankton and small nekton may be entrained in the water flow in both the shallow and deep intake pipes and will leading to high mortality rates due to rapid temperature and pressure changes. Living Organisms maybe impinged against screens on the shallow water intakes if their burst swimming capacity does not overcome the current in pipes generated by the system operation[304]. One of most prominent environmental concerns for OTEC power systems is the potential for upwelled nutrients to fertilize surface waters and cause a phytoplankton bloom. Most of the variability in chlorophyll generally takes place below 44m in Hawaiian [304]

4.27. Wave Energy

Wave energy is based on the fact that any device floating on the surface of sea water experiences an undulating or up- and-down motion due to action of the waves in a motion that can be used to drive an electric generator. This generation has been demonstrated in experimental plants, but the equipment required for the installation is complex as it requires special materials. Wave power technology is not yet mature and hence the is not commercially mature [433].

4.28. Tidal Energy

Electricity can be produced by movement of ocean water having a significant vertical difference between low and high tide. In a simple tidal power plant, a tidal dam is built, and a water turbine installed in the wall so that as water fills the dam during the rising tide a turbine is rotated electricity. As the tide recedes the turbine rotates again generating more power. An effective tidal power station should have a vertical difference between the low and high tide of 10 m or more. Tidal power is renewable, but a barrage or tidal wall can have a significant impact on the ocean environment. Feasible marine sits are scarce with South Africa having no suitable marine locations for power generation, although advances in technology can make more sites feasible for tidal power generation[433].

Tidal streams are easy to predict since they are generated by the rise and fall of the sea level resulting gravitational forces of the moon, sun, and earth. The main challenge of tidal streams is their relatively slow speed, and the problem associated with turbines development which have a sufficiently low cut-in speed to initiate early power generations. The first-generation tidal farms need 2.5 m/s of current to start making them economically viable in restricted geographical places. Tidal current power stations can be used as base load technologies if they are efficiently distributed.

The wave and tidal stream energies combined can potentially supply up to 20% of the of power demand for the United Kingdom which is 30 to 50 GW installed capacity, but just a small portion is either developed or planned or development [461]

4.28.1.Environmental Impacts

Development of tidal power generation may lead to negative environmental impacts during the full life cycle of the power plants. There are limited studies on the lifecycle assessment of for tidal power and marine energy technologies in general. Offshore operations, which include installation and maintenance, account for about 28% of total greenhouse gas emissions, with maintenance contributing to 50% of these emissions. Studies on impacts of 83 tidal devices and installations applying different tidal technologies by performing LCA on 83 tidal devices retrieved from the Joint Research Centre's (JRC) established that phytoplankton dynamics and benthic communities were unlikely to be altered by operations related to tidal power. [461].

Studies showed that a base-case 12 MW array of DG500 prototypes gives a global warming potential (GWP) of 26.3 g CO₂-eq/who. Most emissions in the life cycle assessment of tidal power generation are emissions associated with the production of the foundations, spare parts, and the plant maintenance operations and their impacts can be significantly reduced by recycling. Tidal power generation has much less impact than fossil fuels and is within the range of other renewables making tidal power generation environmentally competitive. The environmental impact of a tidal power plant to the point of grid delivery is generally linearly dependent on the power plant capacity factor while actual power generation is a function of local conditions. The capacity factor capacity factor is considered as 46% (2 GWh/year per DG500 kite) for the base case scenario based on prototype testing and tidal current conditions measurements at the Holyhead site. Modelling a set of scenarios with different design options and various sensitive parameters showed a moderate variations of emissions results, indicating up to 16% (22.0 g CO₂/kWh) lowered impact compared to the base case based on the same capacity factor[461]

4.29. Biomass Energy Sources

Biomass is an organic renewable material derived from plants and animals with potential use to produce fuel, energy, and other products. The main sources of biomass are wood and wood processing wastes, energy crops, agricultural crops and waste materials, municipal solid waste, animal manure, and human sewage. Biomass energy is exploited by burning or conversion to release the stored chemical energy from the sun[184]. Natural materials from living or recently dead plants, trees and animals, have significant potential use as fuel and in industrial

production, especially in the generation of electricity[184] Biomass can be used in many forms to generate heat and power e.g. cofiring with coal, Biomass can be used in different forms e.g. forest residues, straw in form of bales or processed forms like chopped straw, and pellets. Palletisation, improves the bulk and energy density of the biomass for use in cofiring and biomass combustion plants but it increases feedstock cost compared which may negatively affect the cost of power generation [462]. This section presents solid biomass often used by direct combustion.

Biomass includes woody or herbaceous organic materials from forests, cultivated crops, or agricultural wastes. Biomass absorbs carbon dioxide during photosynthesis and is released during combustion or digestion. As an energy resource, biomass has wide range of applications like in co-fired power plants that consume coal and biomass. Power plants. Other examples of applications include the sugar industry where bagasse from sugar cane is used as a fuel for steam generation and power production in sugar factories. This is however discussed separately in chapter in chapter 8 on bagasse and trash and chapter 9 on bagasse co-generation.

4.29.1.Global Potential of Biomass

Biomass resources offer immense opportunities global energy and environmental issues because it has significant energy potential for production of energy resources like biogas, producer gas, methanol, ethanol etc. with many possible applications like heat generation, electricity production, transportation fuels production and applications among many other pathways and options[164, 275]. Biomass has significant energy potential and a wide range of applications globally. In 2018, a total of 637 Terawatt hours (TWh) of electric power was generated globally from biomass with solid biomass accounting for 66% (420 TWh), municipal and industrial waste 19% (121 TWh), and biogas 14% (89 TWh) of total biopower. In the same year, 160 billion liters (bl) of biofuels were derived from biomass with North and South America accounting for 75% while Europe accounted for 14% of global biofuel production[184].

Technologies that conserve resources and revenue in agriculture are crucial to achieving sustainable food and energy production[463]. Coal, oil, and gas account for over 60% of global electricity generation, but renewables are steadily increasing their proportion, from 26% in 2015 to 28% in the first quarter of 2020, with variable renewables increasing from 8%

to 9% during the same period [464]. Since 1990, the proportion of worldwide electricity output that comes from renewable sources has increased by an average of 2% per year, faster than the annual increase in electricity demand (1.8%). When compared to the annual capacity increases of solar photovoltaics (36.5%) and wind energy (23.0%), biogas's 11.5% ranked third fastest. The substantial role played by biomass in global energy generation is evidenced by the 9.7 percent annual growth rate of biofuels since 1990 [465]. Particularly, the relevance of biogas in agriculture and food production cannot be overemphasized. Beyond providing food for all of humanity, agriculture is the primary source of income for more than two-thirds of the world's population. In addition, nearly 82% of the global population is directly or indirectly involved in smallholder agriculture and other industries, making this economic activity the mainstay of many developing countries [463]. This shows that biogas is crucial to the energy transition and that agriculture and other carbon transformative processes should boost its production and consumption[101].

4.29.2.Levelized Cost of Energy For Biomass

The incremental costs of power from biomass shows a steady increase in the incremental costs when cofiring levels increase for each biomass feedstock,. The forest residues tend to have the lowest incremental costs for all cofiring levels. The increase in incremental cost of electricity is due to varied biomass delivery costs and transportation costs that are related to some biomass used in co firing [462]. The levelized cost of energy for biomass ranges from 40.5 to 46.3\$ MWh⁻¹, Maintenance, base fuel (coal), and biomass delivery costs (sum of harvesting, transportation, biomass field cost, road construction, silviculture, and nutrient replacement) are main cost components of the LCOE for the raw biomass cofiring scenario. [462].

The cost of power from biomass generally ranges from 71 to 83 \$ MWh⁻¹ with Forest residues having lowest power costs in many places followed by wheat straw and woodchips. These costs vary from one place to another and one installation to another. Figure 4-3, shows the cost of biomass power.

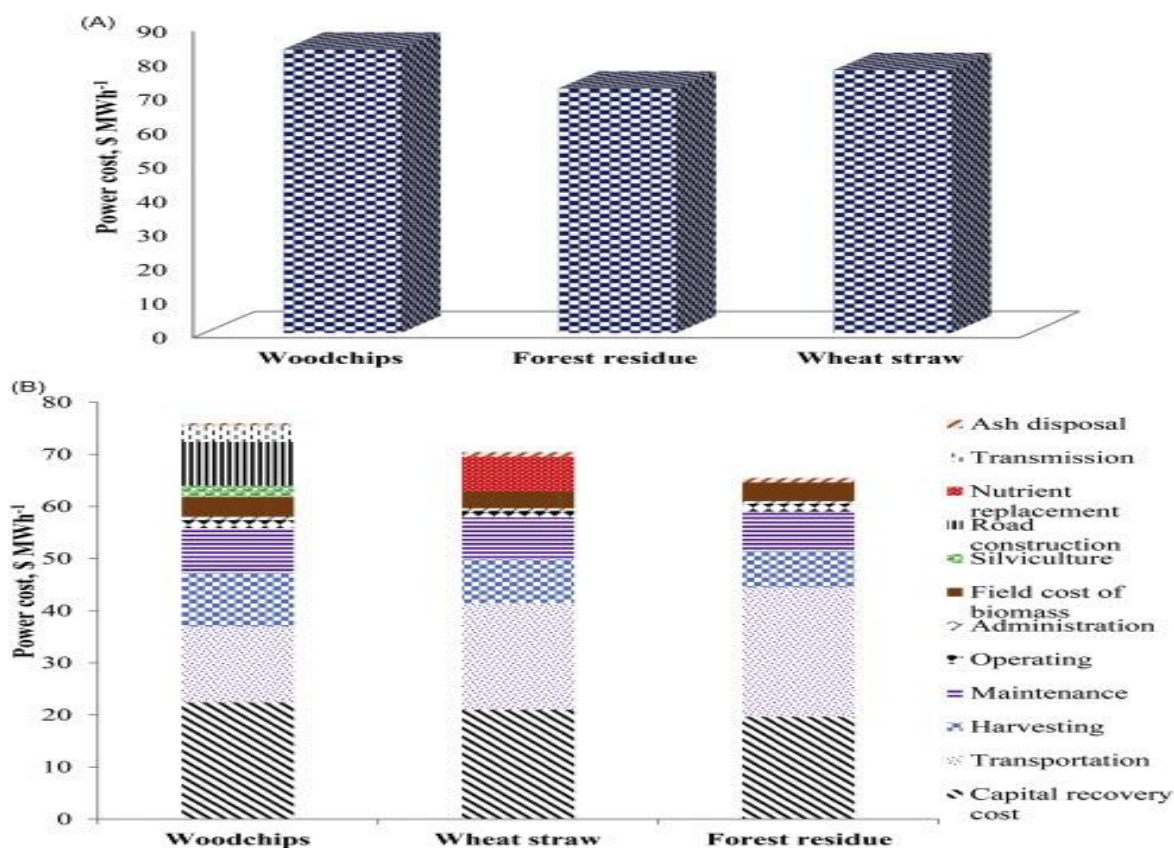


Figure 4-3: Cost of biomass power

From Figure 4-3, it is noted that the main components of biomass power cost are the cost of capital, transportation of biomass, cost of harvesting, and plant operations and maintenance costs.

The carbon abatement costs, which are the costs of avoiding a ton of CO₂ through the replacement of coal or fossil fuels depends on the cofiring scenario at play. The cost of avoiding 1 ton of CO₂ increases as the cofiring increases and forest residue tend to have the lowest abatement costs of 17–25 \$ ton⁻¹ CO₂ for all cofiring levels. This trend follows the trend for the incremental cost of electricity and the biomass delivery costs for each cofiring level[462].

4.29.3.Environmental Impact of Biomass

Biomass power plants emit more CO₂ from their smokestacks while other emissions include particulate matter (PM), carbon monoxide (CO), hydrocarbons, oxygenated organics, free radicals, and chlorinated organics, which are all health hazards. Additionally, cutting trees for

use in power plants speeds up deforestation and reduces the number of trees that can capture our CO₂ emissions hence reduce the natural carbon sequestration). Studies show that it will take decades to well over a century to start receiving the climate benefits provided by biomass, which is well outside the timeframe of averting our current climate crisis[184].

4.29.4.Lifecycle Emissions

On a life-cycle basis, regular biomass energy emits 230 grams of CO₂ equivalent per kWh (230 gCO₂ per KWh), which is one of the highest amount of emissions among renewable sources of energy. Through co-firing biomass energy, can be used with other energy sources like coal boilers, to emit about 740 gCO₂ per KWh, which is higher than average biomass but less than to coal[184].

The total life-cycle emissions of raw biomass for a biomass power generation vary with sources. The total emissions include emissions from biomass production, transportation, construction, and decommissioning, but the computation assumes that there are no emissions from the biomass energy conversion. Production emissions are assumed to be 28 g kWh⁻¹ and construction and decommissioning emission are estimated at 12 g kWh⁻¹ for most biomass feedstocks. Transport related emissions vary with biomass and other factors but can be averaged at 13.4, g kWh⁻¹ for forest residues 6.1, g kWh⁻¹ for woodchips and 11.4 g kWh⁻¹ for wheat straw for transportation distances of 137, 47, and 161 km. Woodchips from whole trees have the lowest emissions due to limited distance of transportation [462]. Figure 4-4 shows the lifecycle emissions for various biomass products.

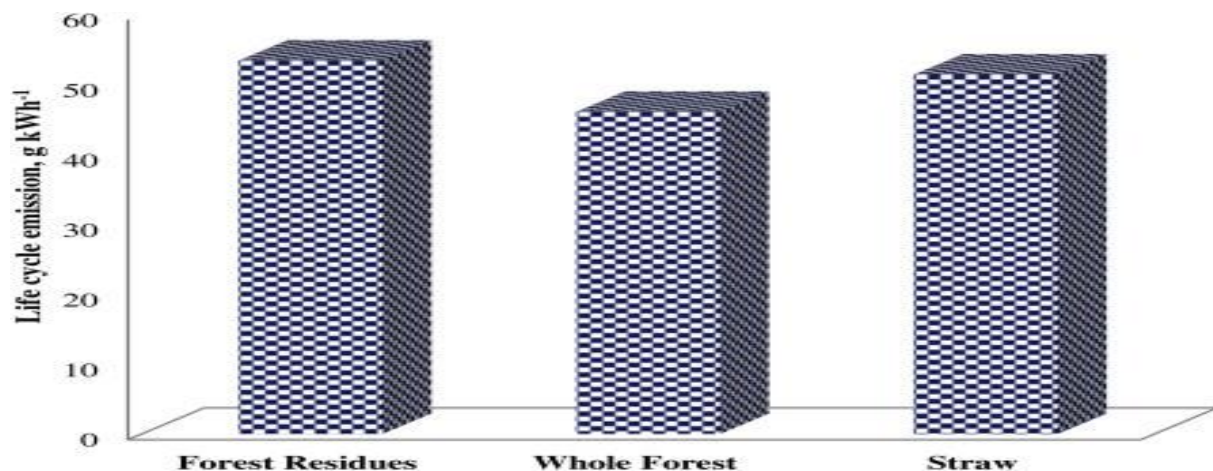


Figure 4-4: Lifecycle emissions of biomass

From Figure 4-4., it is noted that the main factor in biomass life cycle costs are transport costs, production and decommissioning related costs.

4.30. Biogas

Biogas is competitive, viable and generally sustainable energy resource due to abundant supply of cheap feedstocks and availability of a wide range of biogas applications in heating, power generation, fuel, and raw material for further processing and production of sustainable chemicals including hydrogen and carbon dioxide and biofuels. The capacity of biogas power has been growing rapidly for the past decade with global biogas generation capacity increasing from 65 GW in 2010 to 120 GW in 2019 representing a 90% growth. This study presents the pathways for use of biogas in the energy transition for power generation and production of fuels. Diesel engines, petrol or gasoline engines, turbines, microturbines, and Stirling engines offer feasible options for biogas to electricity production. Biogas fuel can be used in both spark ignition (petrol) and compression ignition engines (diesel) with varying degrees of modifications on conventional diesel engines and petrol engines. In internal combustion engines, the dual fuel mode can be used with little no modification compared to full engine conversion to gas engines which may require major modifications. Biogas can also be use in fuel cells for direct conversion to electricity and a raw material for hydrogen and transport fuel production which is a significant pathway to sustainable energy development.

The composition of biogas is determined by feedstock used and the production pathway applied[466]. The main pathways and technologies for biogas and hence biomethane production are the use of bio-digesters, landfill gas recovery systems and wastewater treatment plants. Biogas generally contains between 30 and 70% methane (CH_4) and 30–50% carbon dioxide (CO_2) which varies based on substrate used and to the digestion process control. Other common biogas constituents are hydrogen. The heating value of biogas typically varies between 21–24 MJ/m³ or 6 kWh/m³ [436, 467, 468]. The production of biogas is discussed in the waste to energy conversions.

4.30.1.Composition and Energy Potential of Biogas

Biogas can be used as a fuel or as a raw material for production of chemicals, hydrogen and/or synthesis gas etc. Other than methane and carbon dioxide as the main constituents of biogas,

common contaminants present as trace elements include ammonia (NH₃), moisture, hydrogen sulfide (H₂S), nitrogen (N₂), methyl siloxanes, oxygen, halogenated volatile organic compounds (VOCs), hydrocarbons and carbon monoxide (CO). Some of the trace elements significantly affect biogas as a fuel and must be removed for quality purposes. They include hydrogen sulfide and carbon dioxide. As a fuel, biogas in form of biomethane, biogas upgrading has high operating costs and energy consumption which needs to be addressed [469].

Biogas is a mixture of several gases mainly 30-80% methane, 20-45% carbon dioxide, 2-8% water vapor, effluent and trace gases consisting mainly of O₂ N₂, NH₃ H₂ H₂S [470, 471]. According to [472], raw biogas typically contains CH₄ (40–75%) and CO₂ (15–60%) as the two main components, but with several trace elements like H₂S (<2%), water/moisture (1–10%), nitrogen (0–8%), ammonia(NH₃) (<1%), oxygen (<1%) and CO (<0.6%) and siloxanes (<0.02%).Table 4-3**Error! Reference source not found.** shows the average composition of biogas.

Table 4-3: Average composition of biogas [442, 470, 472-475]

	Element	Composition (%)
1	Methane	30-80
2	Carbon dioxide	15-60
3	Nitrogen	1-10
4	Ammonia	0-0.05
5	Moisture	1-10
6	Hydrogen	0-3
7	Hydrogen sulphide	0.1-0.5
8	Oxygen	0.1-3

9	Ammonia	0-0.5
10	Silicone/siloxanes (R_2SiO)	0-0.5 mg/m ³
11	Carbon dioxide (CO ₂)	0-0.6
12	C _x H _y	0-1

From Table 4-3, it is noted that methane and carbon dioxide are the main constituents of biogas, and its composition generally varies from 30 to 80% based on the quality of the feedstock and process control. Methane is followed by carbon (CO₂) whose composition by volume varies between 20-45%. Other common impurities are nitrogen, ammonia, oxygen, hydrogen sulfide etc.

Variation in the composition of methane also implies that the lower heating value of biogas also varies generally between 16 MJ/m³ and 28 MJ/m³. Although biogas can be used directly in its raw form for generation of heat, electricity and cooking, the thermodynamic and chemical properties are significantly improved through enrichment. Biogas with an average composition of 60% methane and 40% carbon dioxide at 0.1013 MPa and 273K biogas has the following thermodynamic and physical properties summarized in Table 4-4.

Table 4-4: Biogas Properties [471, 476, 477]

	PROPERTY	SYMBOL	VALUE
1	Specific heat capacity	C _p	2.165 kJ/kgK
2	Molar mass	M	16.04
3	Gas constant	R	0.518 kJ/kg
4	Normal density	g	1.2 g/l
5	Critical density	g _c	320 g/l
6	Relative (to air) density	g _r	0.83
7	calorific value of biogas	LCV	22.6 MJ/m ³
8	Critical temperature	T	-2.5°C

9	Critical pressure	p	7.3- 8.9 MPa
10	Flammability limit content in air	v	6-12%
11	Ignition temperature	T	650-750 °C

From Table 4-4, it is noted that the normal density of biogas is about 1.2g/liter and average calorific value is 22.6 MJ/, molar mass is 16.04 and specific heat capacity of 2.165 kJ/kgK while ignition temperature of biogas is between 650 to 750 °C.

4.30.2.Biogas as a Sustainable Energy Resource

The heightening need for food and energy resulting from the growth of the global population, particularly in developing countries, has intensified the strain on energy production and consumption. This strain is currently associated with the release of greenhouse gases and the subsequent impact on climate change[463]. Although biogas has a great deal of promise to supply clean energy to both rural and urban populations, the prevalence of inoperable and abandoned biogas facilities has raised concerns about the sustainability of the technology. This poses questions concerning the dependable creation, distribution, and use of biogas fuel. [478, 479]. It is technically possible to convert this waste into valuable energy sources, thereby generating additional revenue[100, 320, 480]. The challenges facing biogas applications include lack of technical know-how, limited or lack of incentives and subsidies to make biogas competitive by several countries, and the low calorific value and presence of harmful impurities in biogas. These challenges can be addressed by developing and accessing appropriate and affordable biogas technologies, development of a comprehensive policy on construction and operation of biodigesters biogas utilization and sustainable diversification in biogas energy products and services[28, 34, 62].

There are significant socioeconomic benefits of biogas production particularly to the rural areas and communities in the sustainable energy transition through promotion of decentralized generation Biogas cogeneration provides a sustainable option for electricity and heat production of heat and power that can be commercially exploited as a source of revenue from sale of excess electricity to the grid, production of biomethane for injection to gas grids and use as a feedstock industrial production of sustainable fuels ad chemicals like methanol and hydrogen fuel [481, 482]. A vibrant biogas industry also provides significant

opportunities for the growth of energy equipment manufacture, sales and service like plastic tanks, water and gas pipes, valves, cables, etc. making it a significant contributor to local and international economic growth and development.

Raw or cleaned biogas which is free from harmful contaminants has significant energy value and applications. To multifunctional uses of biogas produce include the production of biofuels and renewable energies, reduction in greenhouse gas emissions mainly methane and carbon dioxide, reduction in nuisances resulting from odors and flies associated with uncontrolled biodegrading of biomass, economic or financial savings for farmers, sustainable waste treatment and recycling of organic waste, minimization of water and air pollution, rural poverty alleviation, better of social conditions of rural or remote settlements like gender balance as women who bear the responsibility of looking for firewood are relieved of the struggle and conservation of forests and vegetation cover due reduced use of firewood and charcoal [483]. **Error! Reference source not found.** shows the position of biogas production and use in the circular economy.

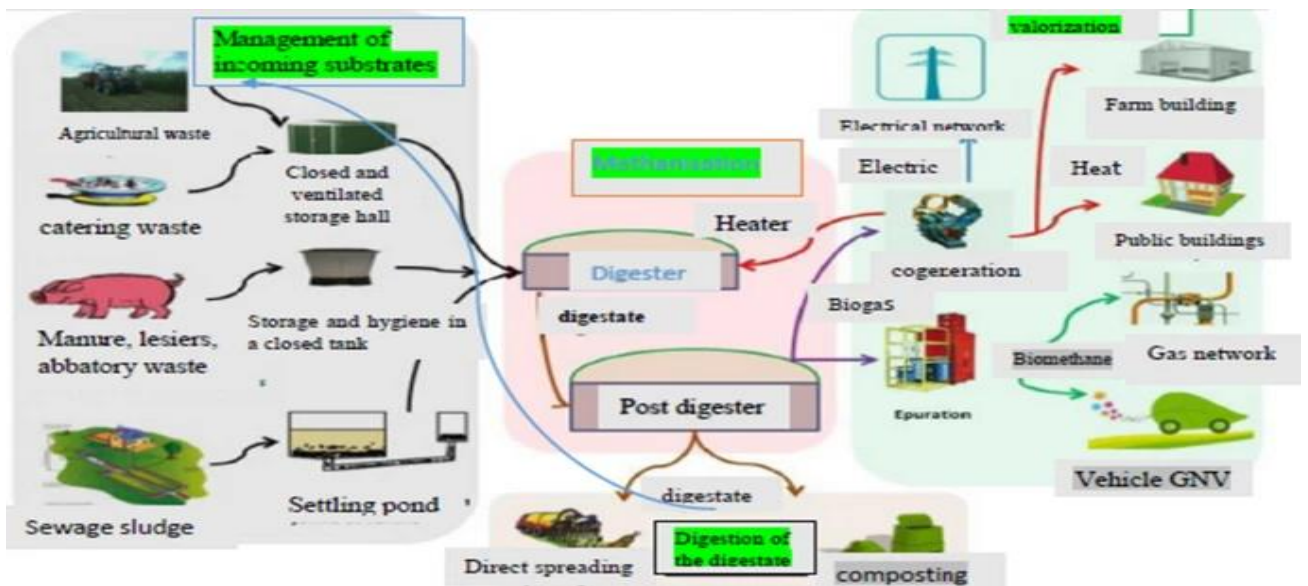


Figure 4-5: Biogas in the circular economy

From **Error! Reference source not found.** it is noted that biogas production has a central role in the circular economy by receiving both agricultural and livestock waste as well as sewage waste which prepared and fed into the digestors which produce digestate and biogas. Digestate is used in farmlands as fertilizer. Biogas has numerous applications adding value to the energy, heat and chemical industries as fuel and feedstock. Upgrading to biomethane makes it

ideal for use as vehicle fuel and substitute for natural gas in gas networks. Therefore, biogas production and use have significant value addition to the environment and economy leading to numerous social benefits to the community.

Without biogas production, to use agricultural and livestock wastes to fertilize the land, farmers will spend money to dispose waste and additional use money to buy processed or chemical fertilizers. On the other hand, in a circular economy, manure and agricultural wastes are used for biogas and digestate production which brings benefits not only for the preservation of environmental resources, but also for the economic benefits for the farmer and the biogas producer[483].

Biogas production, upgrading and use has less environmental impact but is still associated with some greenhouse gas emissions like CO₂, CH₄ and N₂O whose quantities depend on the technology applied and the source of biogas or feedstock used. Biomethane use can reduce the negative environmental impact and pollution potential while anaerobic digestion and gasification used to produce biogas and syngas can be used for hygiene and of bio wastes further keeping the environment clean and healthy [473, 484, 485].

4.30.3.Biogas Applications

Biogas has many benefits and applications which include use in production of biofuels and renewable energies, reduction in greenhouse gas emissions, reductions in odors and flies which are generally associated with uncontrolled biomass biodegrading, financial savings and revenue from biogas derived energy products like electricity and biomethane, waste treatment and recycling of organic waste, reduced air and water pollution, alleviation of rural poverty, better of social conditions of rural or remote settlements which include gender balance since the women who mainly bear the responsibility of looking for fuel will have an opportunity to engage in other tasks and while forests and vegetation will be conserved due to reduced use of firewood and charcoal[16, 28, 39, 62]. Figure 4-6 shows pathways for biogas use as a renewable source of energy.

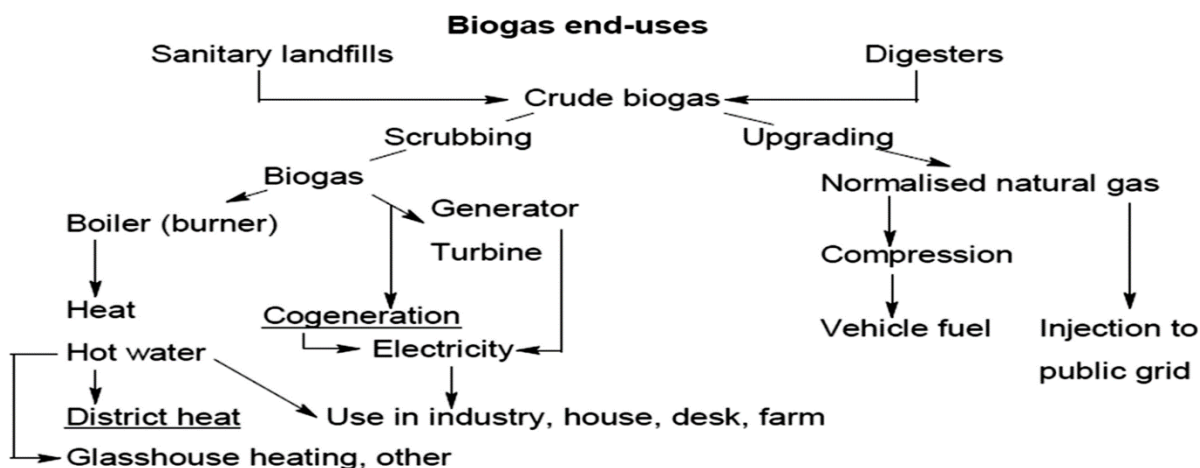


Figure 4-6: Biogas applications

From Figure 4-6 it is observed that upon cleaning and purification, biogas has got many applications like bio-CNG applications, CNG, heat and production, reforming to produce syngas and fuels by the Fischer-Tropsch (FT) Process. Other energy and process products are methanol, ethanol, higher alcohols, and gasoline.

Diesel engines, petrol or gasoline engines, turbines, microturbines, and Stirling engines offer feasible options for biogas to electricity production. Biogas fuel can be used in both spark ignition (petrol) and compression ignition engines (diesel) with varying degrees of modifications on conventional diesel engines and petrol engines. In internal combustion engines, the dual fuel mode can be used with little no modification compared to full engine conversion to gas engines which may require major modifications. Biogas can also be used in fuel cells for direct conversion to electricity and a raw material for hydrogen and transport fuel production which is a significant pathway to sustainable energy development. Biogas can be used directly for cooking and lighting as well as for power generation but can also be used for production of the Fischer-Tropsch (FT) fuels. Fuels are manufactured from biogas by cleaning, and purification before reforming to syngas, and partial oxidation to produce methanol which can be used to make gasoline. Syngas is used in the production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process[34, 62].

4.31. Biomethane

Biogas is a product by anaerobic digestion process with many applications as a renewable energy resource. The main component of biogas with energy value is methane gas, but biogas

has impurities like moisture, carbon dioxide, siloxanes, hydrogen sulfide, siloxanes, hydrocarbons, oxygen, ammonia, oxygen, carbon monoxide and nitrogen whose presence is undesirable as they reduce the calorific value of biogas, while some impurities create operational problems in the energy systems. This necessitates biogas cleaning by application of multi-stage technologies to produce upgraded biogas called biomethane. Biomethane gas is a flexible and easy to store as a fuel with similar properties and applications as fossil natural gas without any need to modify the energy equipment settings for natural gas devices and equipment. Through enrichment, biomethane is manufactured for industrial and domestic applications ranging from thermal and power generation and feedstock for processes like the Fischer-Tropsch (FT) for fuels manufacturer and direct power generation in hydrogen or biogas fuel cells. Biomethane production processes from biogas upgrading includes the pressure swing adsorption which has an option of temperature swing adsorption, absorption technics based on amine, membrane separation, cryogenic separation, and biological separation. Biomethane is an ideal substitute for natural gas and can be used for production of green hydrogen. Hydrogen has a significant potential to play an important role in decarbonizing hard-to-electrify sectors of the economy, e.g., long-distance trucks in transport, aviation, and heavy manufacturing industries. Therefore, biomethane promises to play a leading role in the energy transition through hydrogen, electricity, and other renewable fuels production.

Biomethane can be produced through gasification or anaerobic digestion and upgrading of biogas which are technically and economically different. Anaerobic digestion involves decomposition of complex organic matter in absence of oxygen by action of anaerobic microorganisms, in a low energy demand of heat and electricity making it highly energy efficient[422]. However, the anaerobically produced biogas has got a high fraction of carbon dioxide which has to be removed through various upgrading techniques to produce biomethane with purity of biomethane i.e. >95vol%. The main challenge with biogas upgrading to produce biomethane is the high cost of common technologies like water scrubbing, pressure swing adsorption, chemical absorption etc. mainly because of the use of either energy, chemicals, or both.

Gasification of biomass is another efficient pathway for biomethane production which starts with the production of syngas. Syngas can be used directly to produce power, heat, and fuels,

such as hydrogen and ethanol, but can be processed to produce biomethane. However, methane content in syngas is low and normally requires a methanation process which converts CO and H₂ to CH₄. Water-gas-shift (WGS) process is also needed before methanation, to control the C/H ratio of syngas. Combination of WGS and methanation processes reduces the overall efficiency of gasification, complex system configuration and higher investment and operation costs. The advantage of gasification over anaerobic digestion is the ability of largescale production of biomethane. Gasification and anaerobic digestion principally use different but there is a general a trend to apply gasification to recover energy from waste like as the municipal solid waste, agricultural waste, sludge, which can still be anaerobically digested [422].

Many studies have been undertaken on the anaerobic digestion integrated with biogas upgrading and biomass gasification integrated with methanation; but little attempt has been made at making a comprehensive comparison about two approaches in biomethane production making it difficult to identify the best method for biomethane production from the energy output and conservation perspective making the two technologies equally available for exploitation for now [422].

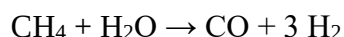
Biomethane is upgraded form of biogas with wide range of applications like replacement of fossil fuels for heat and steam, electricity generation and cogeneration, vehicle fuel, and feedstock for manufacture of bio-based chemicals and substrate in fuel cells, starting reactants in chemical processes, natural gas substitute for industrial and domestic application as well as injection to natural gas grids. The Biomethane technology market is a promising venture globally mainly due to the existence of mature production, conversion technologies and applications. Biomethane has significant flexibility for domestic and industrial scale production and use and is promising to be a leading economical alternative to produce renewable bioenergy.

The existing state-of-the-art biogas purification and upgrading methods are presented in chapter 13.

4.32. Syngas and Producer Gas

Syngas is made by gasification of hydrocarbon feedstock like plants biomass or pyrolysis of carbonaceous waste products [486]. Syngas can be made by steam reforming or partial

oxidation of natural gas or liquid hydrocarbons, or coal gasification. The process of methane steam reforming is endothermic reaction and requires 206 kJ/mol of methane:



Biomass and related hydrocarbon feedstocks can be used to produce biogas and biochar in gasification facilities to produce a gas rich methane and carbon dioxide which is also referred to as *syngas* but whose composition is different from fossil fuel derived *syngas* [486].

4.15.1. Composition and properties of Syngas

The chemical composition of syngas is influenced by the feedstock materials and the processes applied with syngas derived from coal gasification consisting of 30 to 60% carbon monoxide, 25 to 30% hydrogen, 5 to 15% carbon dioxide, and 0 to 5% methane and a smaller number of other gases. This syngas has got less than half the energy density of natural gas.

The syngas composition is affected by operational parameters in syngas production include gasification time, the type and flow rate of gasifying agent (GA), the temperature, the moisture content of the feedstock. Other factors affecting syngas composition size, shape and density of the organic waste used as feedstock[487].

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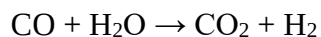
Biomass gasification is an important technology for wider use of biomass as a source of energy. Gasification is a thermochemical conversion process done in limited supply of oxygen to produce a gaseous mixture called syngas which consists of mainly of hydrogen and carbon monoxide [463]. Carbon conversion rate is the key measure of the efficiency of gasification process. For a circulating fluidized bed gasifier, maximum carbon conversion reported is 98–99% [463]. Gasification is a mature technology used to convert carbon-rich biomass to useful combustible gas mixtures e.g. carbon monoxide, hydrogen, and methane. Conversion is achieved by reacting biomass with oxygen in air steam, and carbon dioxide at temperatures higher than ($>600\text{ }^{\circ}\text{C}$) [465]. Gasification is classified as a thermochemical conversion process carried out in a limited supply of oxygen to produce a gaseous mixture called syngas made up hydrogen and carbon monoxide. Carbon conversion is a key measure of gasification efficiency. Maximum carbon conversion of a circulating fluidized bed gasifier can be as high as 98–99% [463, 466].

Gasification systems can supply clean products for use as fuel or synthesis gases in environmentally friendly processes [466]. The similarity between gasification and direct combustion is that they perform better with low moisture content of biomass unlike for anaerobic digestion [463]. Gasification provides a pathway towards sustainable renewable energy sources by converting organic, or fossil based carbonaceous materials to produce hydrogen, carbon monoxide, methane, and carbon dioxide. The reaction in gasification normally takes place at high temperatures, usually above 1000°C in limited supply of oxygen and/or steam. The product of gasification is syngas or producer gas whose heating value is 4-6 MJ/kg. Use of syngas is potentially more efficient than direct combustion of the original like bagasse. Bagasse gasification generates some CO_2 , but it is the CO_2 consumed during the growth of the crop rendering it carbon neutral process [467].

4.15.2. Production and use of syngas

The first reaction, which occurs between the incandescent coke and steam, is strongly endothermic, and leads to production of carbon monoxide (CO), and hydrogen(H₂) which is called water gas in older terminology. Upon the coke bed cooling to a temperature that cannot sustain endothermic reaction, the steam is then replaced by a blast of air. The second and third reactions produce an exothermic reaction forming CO₂ and in the process raises the temperature of the coke bed followed by the second endothermic reaction, in which CO₂ is converted to CO. The overall reaction leading to formation of “producer gas” which is the older terminology. Steam is re-injected, followed by air to generate endless series of cycles until the coke is consumed. The energy value of producer gas is lower than that of water gas mainly caused by dilution with atmospheric nitrogen. To avoid the dilution effect, pure oxygen can be substituted for air leading to production of a gas with much higher calorific value[487]..

Addition of more steam is done to produce more hydrogen from this mixture, to enable water gas shift reaction:



Separation of H₂ from CO₂ can be carried out by means of the pressure swing adsorption (PSA), amine scrubbing, and membrane reactors

In an attempt to create carbon neutrality, electricity from renewable energy sources is used to process CO₂ and H₂O into syngas via high-temperature electrolysis. Syngas that is not methanized has lower heating value of 120 BTU/scf. Untreated syngas can be used in power generation by running hybrid turbines which allow for greater efficiency due to their lower operating temperatures, and extended part lifetime. Different types of wastes having high organic carbon can be gasified to produce syngas that can be upgraded. The main limitations of this process are low productivity, CO inhibition and the extreme operational conditions. Catalysts are used to lower the process temperature and boost conversion yield. Ni is the most commonly used catalyst due to high activity, strong CH₄ selectivity and low cost. Others are Ru and Fe catalysts. Use of nanoscale catalysts can improve their activity and stability with promising examples being hydrotalcites and lanthanum oxide[486]..

Biological method can be used to convert syngas to methane through the metabolism of methanogenic microorganisms also called biomethanation at milder temperatures of 35–75 °C at atmospheric pressure. The biomethanation of syngas by microorganisms can take place in two ways namely as a methane precursor, the first uses an acetate pathway using Microbial cells that like *Acetobacterium woodii* and *Enbacterium limosum*. methanogenic bacteria like *Methanosarcina barkeri* convert acetate to methane. The H_2/CO_2 pathway is used in the other pathway. Microorganisms such as *Methanothermobacter thermoautotrophicus* and *Clostridium thermoaceticum* can convert CO into CO_2 . Microorganisms, like *Methanosarcina formicicum*, convert H_2 and CO_2 in syngas into methane. The use of microorganism makes the conversion process more resilient to impurities and is more environmentally friendly. Additionally biological syngas methanation converts CO/CO_2 and H_2 into CH_4 by different biological routes harbored by bacteria and archaea which supports syngas biomethanation independently from the $CO/CO_2/H_2$ ratio . To upgrade the resulting syngas molecules like CO and CO_2 into biomethane using H_2 as electron donor (typically present in syngas), several strategies can be implemented. Methane can be produced from non-converted CO_2 using traditional biogas scrubbing or by methanizing CO_2 with additional H_2 . In gasification, a CO_2 sorbent can be applied to minimize concentration of CO_2 , producing syngas with a higher concentration of H_2 . Hydrogen (H_2) may be generated by renewable electricity and water electrolysis for higher sustainability[486]..

4.33. Chemically Generated Electricity

Through chemical reduction and oxidation reactions with metals immersed in an electrolyte, ionization can occur with the release of electrons. One side or metal electrodes becomes the cathode because the becomes the anode. By connecting a conducting circuit from the cathode to the anode, electrons flow forming an electric current. This is the basis on which a battery is formed, in which several cells consisting of a pair of cathode and anode are connected in series to give the required voltage where the physical area of the electrode surfaces influences the maximum electric current a cell. The cells have a finite life as chemical reactions consume the electrode material in the primary cells which cannot be recharged.

Some cells do not spontaneously generate electricity but can be charged and put to service to deliver electricity till the charge is exhausted but can be recharged again and used. Such

rechargeable cells called secondary cells have wide applications in the automotive industry and in Uninterruptible Power Supply (UPS) systems as energy storage systems and are used to supply a considerable amount of energy to sustain power system stability under transient and emergencies lasting limited duration. A typical example of such a secondary storage system is the 100 MW, 129 MWh lithium-ion battery-storage plant on a wind farm at Hornsdale, in South Australia which is integrated with the wind farm to supply power to the grid when needed most [14].

4.34. Waste to Energy

Waste-to-energy (WtE) or energy-from-waste (EfW) is a process used to generate energy as electricity and/or heat from the primary treatment of waste, or production of fuel from waste. Many waste to energy systems generate electricity and/or heat directly through combustion or production of combustible fuel, e.g. methane, ethanol, methanol, pyrolysis oil from plastic or synthetic fuels. Energy recovery from waste generally involve conversion of non-recyclable wastes into useful heat, electricity, or fuel through processes like combustion, gasification, pyrolyzation, anaerobic digestion and landfill gas recovery. [93, 164, 360]. Waste to energy is discussed in more detail in chapter 10 as a strategy in the global energy transition.

The main barriers to successful deployment of waste to waste-to-energy systems, are economic, technical, operational, and management challenges. Majority of biomass based wastes are currently landfilled which is wasteful use of potential energy resources [489]. Anaerobic digesters are ideal for high moisture-content organic wastes. Anaerobic digestion for biogas and biomethane production has significant potential for food waste-to-energy municipal waste digestion and agricultural waste. There is growing number of systems operating on mixed food waste at central locations and large food producers[489] . A sustainable waste management system is shown in Figure 0-1.



Figure 0-1: Waste management strategy

Waste-to-energy power plants generally burn waste like (MSW) or garbage or trash, to generate steam in boilers to run electric generator turbine. Municipal solid waste (MSW) is a mixture combustible like paper, plastics, yard waste, and wood related materials. Waste-to-energy (WtE) conversion is an important waste management system, but at the same time contributes to the development of green or low carbon energy [490].

Waste to energy contributes to the reduction in greenhouse gas emissions through three mechanisms, namely.

- i. Generating of steam and electricity from waste to energy avoids (CO₂) emissions from fossil fuel-based power plants.
- ii. The waste to energy combustion process removes potential methane emissions from landfill, thereby avoiding any potential release of methane in the future; and
- iii. The recovery of ferrous and nonferrous metals from municipal solid waste by waste to energy is more energy efficient than production from raw materials, hence it is an energy saving strategy [490].

Studies using the life cycle analysis to establish the environmental and energy impacts for various combinations of recycling, landfilling and waste to energy indicate that waste to energy produces the best results with the least environmental impact in terms of emissions of greenhouse gases, nitrogen oxide, fine particulate precursors, etc. Therefore, waste to energy is the best waste management option for both energy and environmental parameters particularly with respect to reduction in greenhouse gas emissions. Application of decision

support tools to the US inventory of waste to energy facilities, that processes about 28 million tons of trash, show that waste to energy industry avoids emission of about 28 million tons of carbon dioxide equivalents that would have been released if waste to energy were not employed [490].

The Intergovernmental Panel on Climate Change (IPCC) identified waste to energy as an important greenhouse gas emission mitigation technology and its significance in preventing greenhouse gas emissions on a life cycle basis and to mitigate climate change has been taken up by different countries that are trying to comply with the Paris agreement targets. In the report by the World Economic Forum of 2009 entitled 'Green Investing: Towards a Clean Energy Infrastructure,' waste to energy is highlighted as one of eight technologies that can contribute to the future low-carbon electricity systems. . In the EU, waste to energy installations do not require permits or credits for emissions of CO₂, because their greenhouse gas mitigation potential has been recognised. Under the Kyoto Protocol, displacement of fossil-fuel-fired power generation and avoidance of methane generation from landfills waste to energy power plants generated tradable credits (certified emission reductions or CERs) through approved clean development mechanism protocols [490].

The Global Roundtable on Climate Change (GROCC), by the Columbia University's Earth Institute which brought together stakeholders from all regions of the world, acknowledged through a statement dated 20 February 2007 that waste to energy is a means to reduce CO₂ by the electricity generating sector and methane emissions from landfill. The GROCC, which brought together high-level, critical stakeholders from all regions of the world, recognized the importance of waste to energy's role in reducing greenhouse gas emissions[490].

4.34.1.Levelized Cost of Energy for Waste to Energy

The levelized cost for waste to energy varies with technology used, geographical location or country, efficiency or performance of the technology and project specific design features. Feasible technologies for waste to energy conversion include anaerobic digestion, gasification and direct combustion which give different results of levelized costs of energy. Waste to energy process can also produce heat and power simultaneously also called combined heat and power (CHP) which further enhances conversion efficiency. Anaerobic digestion and

gasification can also produce gas pipeline grade biomethane. A comparison on the basis of power generation provides good comparative view of how much energy is recoverable from a given mass of waste [489].

The weighted average cost of capital (WACC), or discount rate, is an important input data for evaluation of the LCOE for biomass power biomass based or waste to energy power generation projects [489]

4.35. Hydrogen Fuel Energy

The content of this section is published in conference paper [491], co-authored by the supervisor Prof. Oludolapo. Hydrogen is among the most important low-carbon technologies more so with the introduction of carbon peaking and carbon neutral targets, and enforcement of policies that promote hydrogen energy technology[7]. The application of hydrogen is concentrated in four principal areas, namely: electricity, industry, transport and building heating, as well as use as a feed for industrial raw materials, energy storage and alternative fuels. The demand for hydrogen has been in a steady growth stimulating research into physical component and the integrated energy system with hydrogen. Physical components for hydrogen energy include electrolysers, the hydrogen fuel cell, and the storage and transport carriers[7, 62]. As a very important future energy resources, hydrogen energy is discussed separately in chapter 14.

Hydrogen has a potential to play an important role in decarbonizing hard-to-electrify sectors of the economy, like long distance trucks in transport, aviation, and heavy manufacturing industries. Hydrogen energy leads us in an important direction in the development of clean energy, and the comprehensive utilization of hydrogen energy is crucial for the low-carbon transformation of the power sector. In this paper, the demand for hydrogen energy in various fields is predicted based on the support vector regression algorithm, which can be converted into an equivalent electrical load when it is all produced from water electrolysis. It can be found that hydrogen production through water electrolysis powered by renewable energy can reduce carbon emissions but will increase the demand for renewable energy generators. Appropriate planning of hydrogen storage can reduce the overall investment cost and promote a low carbon transition of the power system[7]..

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Hydrogen is a clean energy carrier that with potential applications in power generation, automotive application as transportation fuel, fuel for industrial boilers, and even for commercial and residential heating. Since most of the hydrogen is produced currently is from catalytic steam reforming of natural gas, which is fossil there is growing need for use of renewable materials [278]

Renewable hydrogen is considered key in the transition towards a carbon-neutral future. This is due to its spatio-temporal storage and sector coupling potential, which has seen it referred to as energy vector. However, many unresolved issues remain regarding hydrogen's large-scale deployment, e.g., least-cost production, optimal facility siting, and overall implications on power and energy systems. Expansion planning provides an option to study these issues in the holistic context of energy systems[6].

4.36. Sugarcane Bagasse

The contents of these sections are published in [59, 64, 296, 390] co-authored by the supervisor Prof. Oladulopo. The sugarcane crop is grown globally under a wide range of climatic conditions, in the subtropical and tropical regions between 35°N in Spain and 35°S in South Africa. The crop has rain requirements of between 1,200 and 1,600 mm/year. If the rain is well distributed, irrigation is not necessary; otherwise, the crop can also be grown under irrigation. There are many sugarcane varieties with different characteristics, but generally, the crop takes 9-24 months to mature for harvest[296]. Bagasse and sugarcane trash as sustainable energy resources are discussed in detail in chapter 8.

About 115 countries globally annually produced over 1.9 billion tons of sugarcane in 2020 for production of sugar, paper, and alcohol for the global markets as well as electricity through cogeneration. Sugarcane is grown in the tropical and subtropical regions and is the world's largest crop by production quantity, with Brazil accounting for 40%. About 79% of global sugar production is from sugarcane while the rest is made mainly from sugar beets. In the year 2017–2018, the sugarcane industry was the world's second-largest crop production industry, which emphasizes the significant socioeconomic role of the sugarcane crop industry globally. In terms of sugar production, India was the largest producer for the year 2021/2022 producing about 36.88 tons of sugar followed by Brazil at 35.35 million metric tons while the global sugar production stood at roughly 181 million metric tons in 2021/2022 period. The processes in the sugar manufacture and auxiliary services for the plant need continuous and reliable energy supply which can be supplied by bagasse through appropriate cogeneration technology. Besides sugar as the main product in many sugar factories, bagasse contains significant energy potential as a combustion fuel for power generation[296].

4.36.1.Sugar and Bagasse Production

Sugar production leads to production of bagasse fuel as a byproduct. The sugar production process is demonstrated in Figure 0-2.

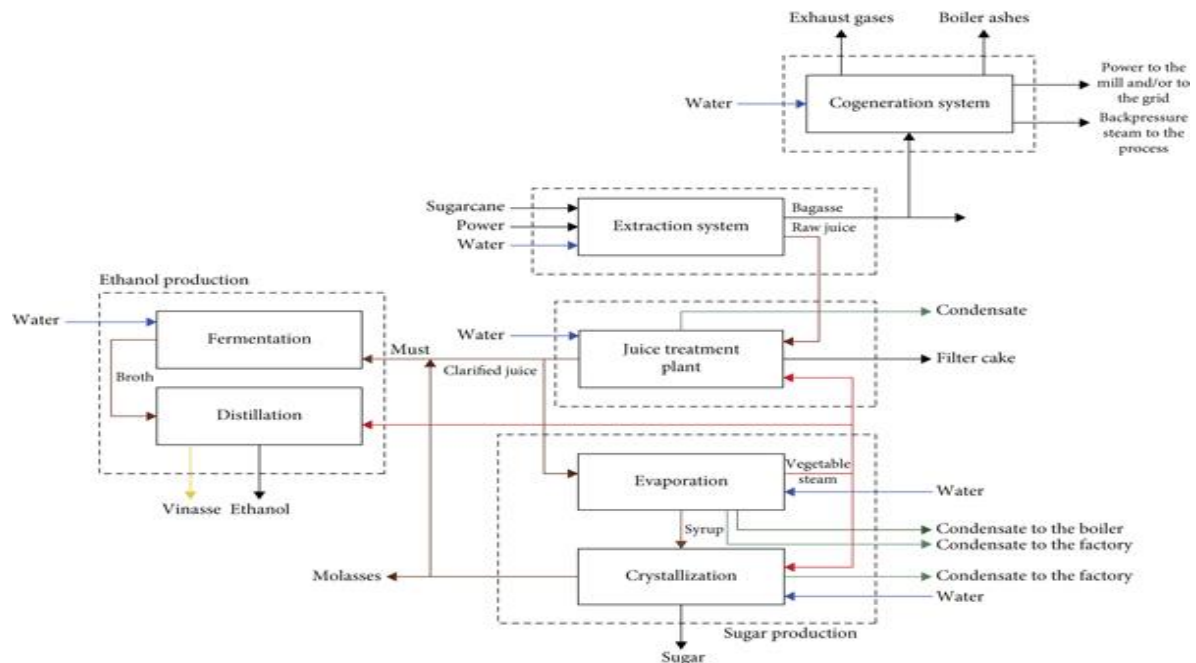


Figure 0-2: Sugar bagasse production process [296]

From Figure 0-2, it is noted that a sugar factory can diversify into ethanol production and power generation from its two main byproducts i.e., molasses and bagasse.

4.36.2. Energy Potential of Bagasse and the Sugar Industry

Sugarcane a leading source of agricultural biomass energy in mainly in the form of sugarcane trash and bagasse. Trash is the field residue left in the field after harvesting while bagasse is fibrous residue leaving the last mill of a sugarcane factory with about 45-50% moisture content. Bagasse mainly consists of mixture of hard fiber, with soft and smooth parenchymatous (pith) tissue which has high hygroscopic property[492]. A typical sugar factory produces sugar as the main product and molasses and bagasse as byproducts with significant energy and economic. As a competitive strategy, one of the most valuable and credible application of bagasse is to convert the sugar mills into electric export based cogeneration power plants[493]. Cogeneration refers to the concurrent generation of electricity and heat for thermal application from the same energy resource. For a sugar factory, heat is needed for process application in centrifuges, evaporators, distillery, clarifiers, sugar dryers, and other processes [1]. The electricity is used in the sugar industry to supplement or substitute grid power to run machines like crushers, pumps, motors, compressors, among others and for heating, ventilation, and air-conditioning. The bagasse produced by a sugar factory has more heat and electricity potential than what a sugar factory needs. Therefore, with proper technology and investment excess electricity can be sold or exported to the grid to earn extra revenue for the sugar factories[81].

Bagasse is the fibrous material left after juice extraction in sugar mills having with average moisture content of about 50%, and with average gross calorific value of 9,731.984 kJ/kg.[493, 494]. In other studies, about 3 kg of bagasse can produce 1 kWh of electricity by means of conventional technologies. The same studies, 1.6 kg of bagasse generate can generate 1 kWh. In yet another study, 1 kWh of electricity needs about 2 kg of bagasse. In conventional boilers with 23 bars and 350°C steam generation, 1 tonne of bagasse can produce 2.2. tones of steam, 11 kg of steam at 23 bar and 350°C can produce e 1 kWh of electricity, however, actual generation of electricity is dependent on technology used and

process steam demand.[81, 493]. In a typical sugar factory generating steam at 23 bars and 350°C, the energy potential is presented in Figure 0-3.

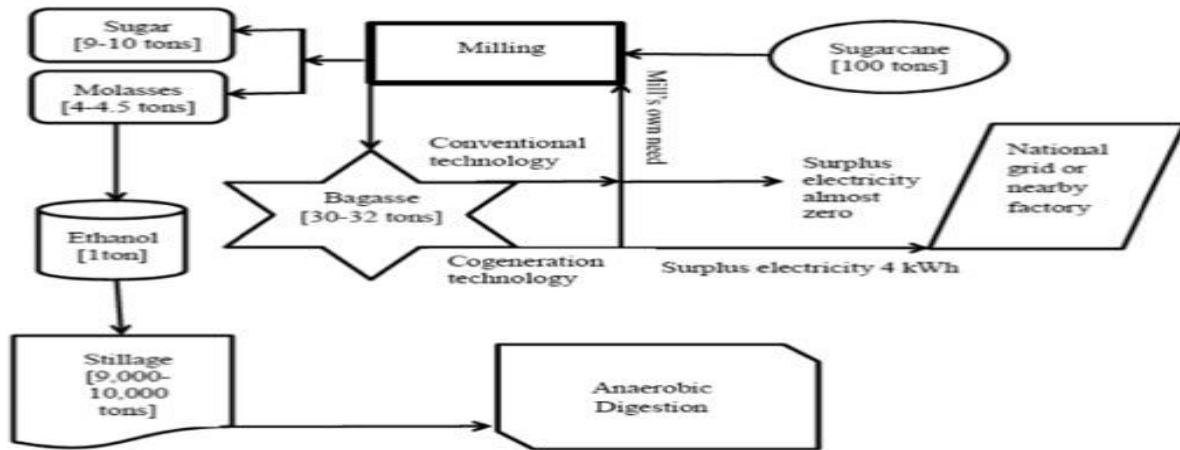


Figure 0-3: Energy potential of a typical sugar factory.[493].

From Figure 0-3 it is observed that in a typical low pressure and temperature sugar factory, 100 tons of cane mailed produce 9-10 tons of sugar, 4-4.5 tons of molasses, I ton of ethanol, 9-10 tons of stillage, and 30-32 tons of bagasse. Therefore, molasses can still provide more bioenergy from the ethanol produced from molasses.

4.37. Magnetohydrodynamic Energy

The MHD system is made up of a heat engine, in which a gas expands from high to low pressure like in a conventional gas turbogenerator where the gas interacts with turbine blade surfaces to drive the turbine to rotate an attached electric generator to produce electricity. In In the MHD system, the kinetic energy of the exposing gas is converted directly to electric energy as it is allowed to expand [88].

Magnetohydrodynamic generation produces energy by means of the interaction of a moving fluid (usually an ionized gas or plasma) and a magnetic field. These systems offer the potential for large-scale power generation with limited environmental impact. Several countries have undertaken MHD research programs since 1970s emphasizing coal as a fuel. MHD energy is also attractive for generation of large electrical power pulses [88]. In a typical MHD power generation system electrically conducting gas is produced at high pressure by combustion of a fossil fuel and directed to through a magnetic field, leading to an electromotive force within it

in accordance with Faraday's law of induction (named for the 19th-century English physicist and chemist Michael Faraday).

Investigation into the MHD started in 1821 by the English chemist Humphry Davy upon showing that an arc could be deflected by a magnetic field. This was followed by , Michael Faraday a decade later who sought to demonstrate motional electromagnetic induction in a conductor moving through Earth's geomagnetic field . Faraday set up a rudimentary open-circuit MHD generator January 1832 or flow meter, on the Waterloo Bridge across the River Thames in London. This study was unsuccessful due to the electrodes being electrochemically polarized, [306].

This led Faraday to pay attention to other aspects of electromagnetic induction, with MHD power generation receiving little attention until the 1920s and '30s, when Bela Karlovitz, a Hungarian-born engineer, first proposed a gaseous MHD system. In 1938 he and Hungarian engineer D. Halász developed an experimental MHD facility at the Westinghouse Electric Corporation research laboratories. It was established in 1946 that seeding the working gas could extract small amounts of electricity. This study was also abandoned, due to a lack of understanding of the conditions necessary to make the working gas an effective conductor[306].

Extensive studies in ionized gas for several applications led to renewed interest in magnetohydrodynamics during the late 1950s. Richard J. Rosa, an American engineer operated the first truly successful MHD generator in 1959 the, generating 10 kilowatts of electricity. Under the direction of the American physicist Arthur R. Kantrowitz, the Avco Research Laboratory, had constructed and operated a 33-megawatt MHD generator by 1963. MHD research faced curtailment in the 1960s due to the assumption that nuclear power was going to dominate commercial power generation, and the failure get applications for space missions. The 1970s, realized a revival of interest, centered around coal-fueled systems, and by late 1980s, it had developed to the point where construction of a complete demonstration system was feasible. Deep investment in MHD by utilities is limited by performance and economic risks, a situation that may change may change if energy prices or environmental considerations shift significantly[306].

Interest in MHD energy was originally stimulated by observations that an interaction of plasma with a magnetic field can take place at much higher temperatures than were possible in a rotating mechanical turbine. The limiting performance in heat engines was established by the French engineer Sadi Carnot which establishes the maximum theoretical efficiency of a heat engine, as the difference between the hot source temperature and the cold sink temperature, divided by the source temperature. By allowing inefficiencies introduced by finite heat transfer rates and component inefficiencies in real heat engines, a system employing an MHD generator provides a potential of an ultimate efficiency of 60 to 65 %, which is higher than the 35 to 40 percent efficiency of a modern conventional steam plant. MHD generators additionally generate less pollutants than conventional plants. The main challenge with MHD energy is higher construction costs and limited adoption of the energy systems [88].

4.38. Summary of Energy Sources

The various energy sources for potential application in power generation are summarized in Table 0-1.

Table 0-1: The various energy sources for potential application in power generation

	Energy resource	Features and composition sustainability	Contribution to the transition and sustainability
1	Hydropower	Hydropower is renewable and is gotten from moving water which runs hydraulic turbines. Hydropower is affected by weather	Hydro has contributed clean power for many years. Significant potential remains in small and mini hydropower schemes in decentralized and centralized generation. Use of storage facilities like dams and pumped storage plants will enhance their use generation
2	Solar Energy	Solar is a variable renewable energy supplied by natural radiations from the sun. the energy is affected by weather	Solar will play a big role in the future transition as a renewable energy resource but development in solar cells technology and smart grids will enhance their uptake

		and may be unpredictable intermittent in some cases	contribution to grid electricity. Energy storage and transition to smart grids will enhance their use in electricity generation
3	Wind Energy	Wind is natural and renewable and can be developed as onshore or offshore wind power stations. The main challenge facing wind power is variability and intermittent as well as large land requirements.	Wind resources are significant but variable in supply. Their huge contributions lie in the transition to smart grids and development of energy storage facilities. Wind power is clean and abundant although variable and intermittent. Smart grids and energy storage will improve their uptake and contribution.
4	Hydrogen	Hydrogen can be made by electrolysis and mainly by steam methane reforming	Hydrogen will play a leading role in development of fuel cells and as a fuel to replace fossil fuels. More research into efficient conversion and handling is needed to generate hydrogen from renewable sources as opposed to use of fossil fuel gases.
5	Biogas	Include biogas, biofuels, energy crops, plant waste, animal waste. Relevant policy measures necessary to make them competitive	Renewable and zero and low carbon sources and can substitute fossil fuels domestic, industrial, transport and power generation. Bioenergy sources include biogas, syngas, gasification, bagasse, bioethanol, biodiesel and other fuels and energy sources of organic origin including energy crops.
6	Biomethane	Produced by upgrading biogas or syngas	Can substitute natural gas in all its applications and can be used to produce hydrogen and power fuel cells
7	Biodiesel		
8	Bagasse	Bagasse is energy rich a fibrous waste solid from cane milling process.	Can be used to generate green electricity for the grid by sugarcane factories

9	Solid Biomass		
10	Geothermal Energy	Geothermal energy has significant potential but huge upfront costs, investment risks and long project delivery tools have kept contribution low	Geothermal has very low actual and lifetime emissions. Has high load factors and capacity factors and hence ideal for base load electricity supply, Increased use of geothermal will reduce electricity price, reliability and cut greenhouse gas emissions. Use of wellhead generators can help mitigate some shortcomings like cost and project duration.
11	Producer gas	Huge quantiles of animals, plants, and combustible industrial wastes most with significant energy potential are produced continuously globally. They include municipal solid waste, agricultural waste, and animal waste like slaughterhouse waste	Various waste to energy technologies exists with more efficient systems being needed for efficient waste to energy conversion. Processes like biogas and biomethane production, direct combustion can be used both for a clean environment, generate green energy and electricity and reduce disposal costs and health risks in a sustainable manner.
12	Nuclear energy	Nuclear power takes many years to develop, guarantees a large supply of low carbon electricity at high load factor and capacity factor. Also, unit cost of power is relatively low.	Nuclear will increase reliability, reduce unit cost of power, and cut emissions. There is a need to increase funding for nuclear energy and reduce the high project duration. Use of small modular reactors for countries with low demand and to facilitate phased development is encouraged for faster growth of nuclear power.
13	Wave energy	This is a renewable energy resource mainly in the form of tidal power, wave	Has very limited contribution globally by will lay a leading role in the transition by

		power and ocean thermal. Ocean thermal is limited by the low thermal gradient over which heat transfer is to take place.	investing in efficient technology for extraction of energy with low thermal gradient in ocean thermal. Policy incentives and funding are necessary to increase generation from wave and tidal power. The main challenge with marine power is that supply is not continuous, but relatively predictable.
14	Tidal power	Tides are caused by the gravitational attraction of the sun and the moon on water	Can supply clean power from tides
15	Ocean thermal	A renewable energy produced by differences in temperature between the water close to the surface and deep waters which are warm	Can produce power by exploiting thermal gradient between cold deep waters and warm surface waters of the ocean
16	Natural gas	Natural gas is nonrenewable source but cleaner than coal, diesel and petrol and global resources are huge	Can substitute heavy polluters like coal and petroleum like diesel and petrol as fuel. The main challenge is delay in the transition to zero carbon target and investment risk involved with the transition.
17	Coal	Coal is nonrenewable and currently the largest source of global electricity. Huge reserves in some countries. Generate ash and carbon dioxide, N ₂ O and SO ₂ hence high environmental impact	Coal produces reliable power but has high emissions. It can stabilize generations. Consumption should gradually be reduced by substitution.
18	oil	Generate high carbon emissions as well as N ₂ O and SO ₂ . High reserves in some countries hence slow transition	With application of efficient generation like cogeneration and blending, can supply limited power and fuel for use

From Table 0-1, it is noted that the world has various types of energy sources to choose from for exploitation in power generation and other uses.

4.39. Chapter Conclusions

Various energy sources are available for direct or indirect use in thermal and power generation. These energy sources can be classified as renewable and nonrenewable, some promising energy sources are still under development in terms of technology maturity like the MHD, ocean thermal, wave energy, tidal energy, hydrogen. Hydrogen which is still under development as an energy carrier has significant potential applications in power generation as a fuel for engines, fuel cells for transport and power generation and energy storage. The main sustainability challenge facing hydrogen energy is that most of hydrogen produced today is from natural gas and coal. Biomethane and biogas have potential application in power generation, transport fuels and fuel cells. Biomethane can be used as a direct substitute of fossil natural gas and can be used in all applications for natural gas. Bagasse fuel is the main energy source for the sugar cane industry as a cogeneration fuel. Bagasse cogeneration technology is mature and can be connected to the grid to supply green electricity.

Magnetohydrodynamic generation generates power by means of the interaction of a moving fluid (usually an ionized gas or plasma) and a magnetic field. These systems offer the potential for large-scale power generation with limited environmental impact, but the technology is not yet mature for commercial deployment. Wind and solar energy remain abundant for use in power generation and other applications but have a challenge of intermittence. Hydropower is the leading source of renewable energy but is also affected by seasonal variation of precipitation while feasible hydropower sites are not always available.

Although nuclear energy is nonrenewable, the Uranium deposits are huge and nuclear is a low carbon energy resource. Its deployment is however limited by concerns over safety and huge capital investment and long project gestation period. Nuclear waste handling remains unresolved challenge for many countries.

CHAPTER 5:

POWER PLANTS AND ENERGY CONVERSION SYSTEMS

5. Overview

This chapter presents the various power plant technologies and conversion systems that can be applied to generate electricity from various energy sources. Both mature and evolving technologies are presented with their potential, applications, and sustainability status. Power plants and conversion systems discussed include diesel power plants, gas turbine power plants, hydropower plants, solar thermal and solar photovoltaic, wind power plants, geothermal power plants, nuclear, coal power plants, biomass, bagasse cogeneration plants, fuel cells, ocean thermal, wave power and tidal power. The contents of this chapter are published in the authors' publications appearing as reference numbers [44, 58, 101, 115, 279, 296, 309, 332, 388, 391, 393, 495, 496].

Based on energy sources, the power plants are broadly categorized into renewable energy-based power generation which use renewable energy sources and 'thermal energy-based power generation. Thermal energy-based power generation technology includes diesel power plants, gas turbines, steam turbines based and combined cycles that use combustion fuel like oil, natural gas, and coal. Nuclear power plants are also called thermal power generation using nuclear fuel to generate steam to run a steam turbine for power generation[39]. Each power generation technology has its specific operational characteristics including economics, efficiency, availability, ramp in and ramp out characteristics, etc. Evaluation and selection of generation or conversion characteristics considers factors like cost of development, emissions, operation, and maintenance costs (O&M costs) and operational constraints[16, 23].

5.18. Coal Power Plants

Coal power plants remain the dominant source of energy for power generation accounting for > 40% of global electricity since the 1970s. Global coal production increased nearly 2.2-fold from 1958 million tons of oil equivalent (Mtoe) in 1980 to 4270 Mtoe in 2010. In terms of energy value, coal production globally was about 174.6 exajoules in 2022 representing an increase of some 7.4% compared to the previous year. Coal production increased by 78 exajoules between 2000 and 2022 [392]. A coal-fired power station or coal power plant refers

to a thermal power station that burns coal to produce electricity. There are over 2,400 coal-fired power stations globally with over 2,000 gigawatts capacity producing almost a third of the world's electricity. Coal power generation is associated with many illnesses and is associated with many early deaths mainly from air pollution[497].

In coal power plants, coal is usually pulverized and burned in a pulverized coal-fired boiler. Coal burns in a furnace then the furnace heat boils water under pressure to produce water to steam, used to run steam turbines coupled to generators for power production. It is therefore the chemical energy stored in coal that is converted into thermal energy, mechanical energy and, finally, electrical energy[162, 497].

5.18.1.Sustainability of Coal Power Plants

Coal power plants, particularly the large-scale plants, are vast facilities that can dominate the landscape due to their towering stacks which are visible from miles away and not many people would wish to live across the street from these facilities usually relegated to industrial areas. Coal being mainly carbon emits CO₂ upon combustion as the primary combustion product, while other pollutants emission are heavy metals, emitted from the stacks in most plants. The application of carbon capture and storage (CCS) emissions is essential to the future of coal. Surface mining of coal is significantly and incredibly destructive to landscapes and watersheds especially with the practice of “mountaintop removal” mining which is common and has devastating impact to the environment[498].

5.19. Diesel Power Plants

The contents of this section are published in authors papers[93, 279, 496]. Diesel power plants use diesel engines as prime movers powered mainly by heavy fuel oil or industrial diesel oil and with potential for conversion to gas engines or dual fuel engines. The global concerns over prices of diesel and heavy fuel oil and energy related greenhouse gas emissions have created demand for natural gas as an alternative fuel for power generation by diesel power stations[280]

Diesel engines have wide applications in power generation for both grid and off grid applications. The plants vary in size and applications which include use as emergency plants, standby plants for main power stations, nursery plants, mobile power plants, and peak power

plants. The strength and wide application of diesel power plants lies in their high load factors, high part load efficiency, ability to quickly start and stop and high fuel flexibility[280]

5.19.1.Design and Construction

Diesel power plants are equipped with generators driven by internal combustion engines as prime movers. Diesel engines are preferred option due to superior qualities like high power density hence smaller engines for higher power output, higher efficiency, cheaper fuel and more fuel flexibility compared to petrol engines [280]. The main limitations of diesel engines are use of higher compression ratios which require stronger and hence expensive structures, production of characteristic knocking sound known as diesel clatter, higher greenhouse gas emissions and high cost of operations and maintenance and size limitations in developing large power stations hence many units are needed for big stations. The diesel engines are also heavier and undesirable for light duty applications like in sports cars. Diesel engine operations are based on the air standard diesel cycle named after its inventor (Rudolf Diesel). The cycle consists of four successive processes realized within two or four strokes of the pistons to complete a cycle. Most engines in operation globally are four stroke engines with varying number of cylinders[93, 279, 280]

Various parts, systems and subassemblies constitute the engines power plants. The main systems are charge air, compressed air systems, fuel system, engine governing system, exhaust system, lubrication system etc. The main parts of the engine include the crankshaft, fuel pumps, camshafts, turbocharger, cylinder head, pistons, etc.. In conventional diesel engines, compression of combustion air is done in the cylinder with valves closed to high temperature and pressure before fuel injection just before the top dead center of the piston. The high temperature of the compressed air initiates combustion. The expanding products of combustion act on the piston which through the connecting rod rotates the crank shaft which coupled to an electric generator for power generation[280].

Internal combustion engines can be powered by natural gas engines in different mods like bi-fuel, dedicated natural gas engines or dual fuel based on engine design. The bi-fuel engines work on Otto cycle engines or spark ignition engines running on both natural gas and gasoline fuel. The dedicated natural gas engines also work on the principle of the air standard Otto cycle but use only natural gas as the fuel, although often they will use petrol as a pilot oil. The

dual fuel engines use the diesel cycle technology and therefore they are technically diesel cycle engines running on pure natural gas as the fuel, although they may be designed to operate with diesel pilot fuel for ignition and in small proportion of the main fuel which is natural gas. The dual fuel engines can run fully on diesel fuel especially on low load conditions including during idling state, but they admit more natural gas with increasing loads often to 80% or more[280]



Figure 5-1: An operating 120 MW diesel engine power plant at Kipevu Mombasa, Kenya [280]

Figure 5-1 represents diesel power plant with main features like the chimneys, oil tanks, power plant buildings etc.

5.19.2.Environmental Impact of Diesel Power Plants

The society energy needs are predominantly met by fossil fuels sources including diesel power plants for grid and off grid power production. The fossil fuels are also used to power, boilers and air-conditioning systems and other heat applications [21]. Fossil fuels have a significant contribution to global primary energy supply, and their overall consumption has increased over the years [330]. The global increase in fossil fuels consumption worldwide is a threat to the environment due to increased CO_2 and hence the danger of global warming besides accelerated depletion of the fossil fuel reserves [51]. Cogeneration in diesel power generation is attractive due to the growing need to reduce consumption through efficient use of resources. Through cogeneration and other technologies, the global energy sector can reduce carbon emissions by between 8.7-18.7% [499].

5.20. Gas Turbine Power Plants

The cycle or thermal efficiencies of the open cycle turbines low because of the mentioned inefficiencies hence the need to increase efficiency by use of advanced cycles like combined cycles Low thermal efficiency, high cost of fuel and environmental concerns associated with fossil fuel sources have set in motion a transition that seeks to increase energy efficiency and increased use of renewable energy sources in power generation. The main limitations of gas turbine plants include They are not self-starting, have low overall thermal efficiency, they have very high rotor speeds hence challenge with balancing, high degree of irreversibility and low part load efficiency[299].

5.20.1.Design and Construction

There are three main parts of a gas turbine plant in addition to auxiliary parts. These basic parts are the compressor, combustor, and the turbine. Auxiliary equipment which includes fuel pumps and fuel system, compressed air system, lubrication oil system, ducts. Modern gas turbine powerplants have modifications by provision of extra features like regenerators, intercoolers, preheaters, exhaust gas boilers, cogeneration steam turbines, based on specific modifications and improvements. Gas turbines plants are further grouped into constant pressure combustion and constant volume combustion gas turbines plants. The constant pressure turbines are either open cycle or closed cycle plants. The constant volume gas turbine operates within constant volume space. The most common design of gas turbines in use are the open cycle type which are basic, cheap, and motivated by availability of readily available cheap fuel sources for gas turbine operation[299].

5.20.2. Simple Cycle Gas Turbines

Gas turbine can operate from both gaseous fuel and liquid fuels and have applications in industry as prime movers and power generation. A simple cycle gas turbine is quick to start and stop s while aeroderivative have additional advantages of higher efficiency, no additional cost on O&M for the start-up and less maintenance downtime. Gas turbines provide high rotating inertia which is essential for power system stability[252].

5.20.3. Combined Cycle Gas Turbine (CCGT)

Combined cycle gas turbine plants consist of gas turbine (GT), have a heat recovery steam generators (HRSG) and steam turbine (ST) for extra power generation based on the Rankine cycle. The HRSG applied Combined Cycle Gas Turbine (CCGT) are tailored specifically for each gas turbine unit but can be configured to and connected multiple turbines. The Combined cycle plants are often characterized with very high efficiencies and are ideal for baseload and intermediate load operations[252].

5.20.4.Application of Gas Turbines

The main application of gas turbines is in power generation, oil and gas industry operations, marine propulsion, and aviation. The gas turbines are used in aviation industry because of their high density while in power generation, they are popular because of limited need of water, low space requirements, quick construction, mobility and ability of quick starting and quick stopping. The gas turbines are popular with oil and gas industry due to their quick installation, high flexibility and mobility and ability of quick installation[299]. The various application for gas turbines includes:

- i. Power generation as prime movers for peak and emergency supply
- ii. Aircraft propulsion
- iii. Use in the marine for ship propulsion.
- iv. Used for field operations in oil and gas development.
- v. Supply of reactive power to the grid

5.20.5.Fuels for Gas Turbines

The specific fuel consumption of kerosene is much lower than that of kerosene due to its high calorific value (48000KJ/Kg) in comparison to that of Kerosene (43000KJ/Kg). Therefore, less amounts of natural gas are used to deliver the same power output in comparison to Kerosene. For the same power output however, kerosene has higher cycle efficiency in comparison to natural gas. The power generation sector contributes one of the largest shares of carbon oxide (CO₂) emissions at about 40%. Gas turbines are key contributors of this percentage due to their use of hydrocarbon fuels. This percentage can be lowered using renewable sources such as natural gas (NG). Due to the high content of hydrogen and carbon

present in kerosene there is a high percentage of unburnt hydrocarbons (UHC) unlike natural gas which contributes to low emissions of unburnt hydrocarbons. Though the emissions of unburnt hydrocarbons is substantially low[299].

Kerosene has a very high content of Sulphur (iv) Oxide which is harmful to humans due to reaction with bodily fluids to form sulfuric acid (H_2SO_4) whereas natural gas has a low Sulphur (iv) Oxide. Natural gas also offers NO_x and soot (carbon) emission reduction when used instead of kerosene which leads to high NO_x and soot production due to high levels of hydrocarbon. NO_x which is normally a combination of Nitric oxide (NO) and nitrogen dioxide (NO_2) which combine to form smog and acid rain and lead to the formation of ground ozone and fine particles which have adverse health effects[299] .

5.20.6.Performance Improvements

Combined Cycle Power Plant (CCPP) needs to be functioning properly i.e., the gas turbine, steam turbine and the Heat Recovery Steam Generator (HRSG) need to be functioning optimally. Various operating parameters such as ambient temperature and compression ratios were seen to have a telling say in the efficiency of the power plant. In a study by [299], it was demonstrated that gas turbine output and efficiency can be increased with overall cycle efficiency increase by 54.2%[299].

It is possible to use high hydrogen content fuels in gas turbine for power generation with CO_2 capture, IGCC plants or using hydrogen from renewables. The main challenge is highly reactive e combustion characteristics which make dilution necessary to mitigate NO_x emissions. High Exhaust Gas Recirculation (EGR) rate can be applied to the gas turbine to generate oxygen depleted air which inherently limits combustion temperature to keep NO_x emissions low without the need for dilution or unsafe premixing[500].

Fuel with high hydrogen has the following in three possible applications:

- i. Use in the Integrated Gasification Combined Cycle (IGCC) power plants.
- ii. Use in power plants applsystems.re-combustion CO_2 capture in a Carbon Capture and Sequestration (CCS) systems;
- iii. Use in power plants in a fully developed renewable energy-based society, with hydrogen applied in storage of excess variable renewables like wind, solar,

Hydrogen fuel is CO₂ free, but its combustion generates high levels of Nitrogen Oxides (NO_x) which is a strongly regulated pollutant that plays a significant role in atmospheric pollution as it is associated with smog and acid rains. NO_x can be formed through a kinetic pathway where the nitrogen oxidized by oxygen in a high temperature environment. Cases of high NO_x values in excess of 200 ppm @ 15% O₂ dry have been noted in an 85–90% hydrogen fuelled GE's 6 F A test combustor and even 800 ppm @ 15% O₂ dry. These values are significantly higher than typical emission limits applied to gas turbines indicating how inadequate the current combustor technology is and therefore the need for innovative solutions to increase the feasibility of use of hydrogen in gas turbines [500].

In modern conventional fossil fuel based gas turbines, premixing of fuel and air before combustion in avoids high temperature regions in the flame to the point that the adiabatic flame temperature of the mixture is much lower than the stoichiometric mixture. The burners are referred to as lean premixed burners or Dry Low NO_x (DLN) burners[500].

5.20.7.Levelized Cost of Energy

The cost of electricity from a gas-fired power plant is a function of the cost of the building the power plants and the cost of the fuel used as well as operation and maintenance. Combined cycle power plants are the most common gas-fired plants and are also the cheapest power plants to construct. The main challenge of natural gas is price volatility which can lead to a heightened level of risk associated with gas-fired electricity generation [9]. The levelized cost of energy (LCOE) for natural gas-fired combined cycle power plant as estimated by Lazard in 2014 was between \$61/MWh and \$87/MWh. hence more expensive than wind[501]. Electricity cost from gas-fired plants can significantly lowered by low-cost power from natural gas power plants. At a 7% discount rate, the LCOE for the gas-fired plant in the US was \$66/MWh but higher in Japan at \$138/MWh. For China, the LCOE at a 7% discount rate was about \$93/MWh over the same period.[501]. Including carbon capture reduces emissions from the gas-fired combined cycle plants but effectively increases the cost of electricity to about \$127/MWh., which is roughly double the lowest LCOE for a gas-fired plant without carbon capture [501].

5.21. Nuclear Power Plants

The content of this section is published in the authors paper reference [502], co-authored by the supervisor Prof. Oludolapo. For a nuclear power plant the most important contributing factor to the cost of electricity is the cost of building the plant and related financing cost. Although nuclear power plants are complex engineering projects and extremely expensive, their long lifetime keeps the cost of power low relative to many other sources [462], [503].

Nuclear power is low-emission source of electricity, accounting for about 10% of global electricity generation. Nuclear energy can complement renewables in reducing emissions and contributing to electricity security as a dispatchable power source. Nuclear energy can also be used to produce low low-emission heat and hydrogen. There is need to get nuclear power on track with the Net Zero Emissions by 2050 Scenario. Lifetime extensions of existing nuclear plants has proved to be one of the most cost-effective sources of low-emission electricity. Other measures include promotion of small modular reactors, which can help expand the range of low-emission options and increase options to net zero power[287].

Nuclear power plants have been in operation for more than 50 years now, during which they have avoided 66 Gt of CO₂ emissions globally by replacing fossil fuel like coal, natural gas, and oil. Developed economies will generate 20% higher emissions over the past 50 years, led by the United States and European Union if nuclear power is abandoned. Emerging and developing markets like China and India have recently increased their nuclear power capacity leading a reduction in emissions by 9 Gt of emissions [287].

Nuclear power generation capacity reduced by about 3 GW globally in 2021 due to retirement of old power plants since new reactors could not compensate for over 8 GW of retirements. All new capacity in 2021 came from emerging markets and developing economies while Germany accounted for the majority permanent shutdowns [287]. To achieve the Net Zero Scenario, nuclear power generation should expand by about 10-17 GW per year to 2030 to reduce fossil fuel consumption while at the same time increase the share of renewable sources of energy in power generation[96, 280]. Measures like prioritising lifetime extensions in G7 will help bolster the low-emissions and make the most of new nuclear power generation capacity. Six large-scale nuclear reactors were commissioned in 2021 with a combined electricity generation capacity of 5.6 GW with most of the new capacity in China [287].

The net zero targets encourage innovation in nuclear power technologies, like use of small modular reactors (SMRs), which smaller than 300 MW per reactor, down to 10 MW. SMRs promise to provide more affordable, and easy and faster to construct compared to conventional large reactors with about 70 designs under development. SMRs can be built in factory and moved to final location, which reduces timelines and construction risks as well as and financing costs. As the share of wind and solar increases, SMRs promise to be key in the transition by meeting rising flexibility needs in the power system. SMRs can also be used for heat and hydrogen production[287].

SMRs success needs policy and regulatory reforms to streamline the licensing and regulatory frameworks. Lessons from the first commercial-scale projects, will help cut down the cost of new nuclear power plant projects. SMRs also require technological advancements for widespread use in decarbonised systems. The Generation III technologies, focusing on enhanced safety, have new concepts under construction expected to come online by 2030. Generation IV SMRs, include liquid metal-cooled, molten salt-cooled and gas-cooled designs, which are less advanced need more development. The ability to reach higher temperatures and potentially recycle used nuclear fuel makes SMRs attractive provided there is progress within required timelines. SMRs may be full commercialised by the mid-2030s, and add significant value to the in decarbonising power systems [287].

Most hydrogen is produced by steam reforming of natural gas or from coal gasification. The demand for large volumes of low-emission hydrogen to achieve Net Zero emissions generates new opportunities for nuclear power through many ways, but the most technologically advanced option is to couple nuclear reactors with electrolyzers while other methods that create hydrogen directly from nuclear power without electrolysis are under development. In high-temperature thermochemical hydrogen production, heat is derived directly from the nuclear unit to split water into hydrogen and oxygen with system efficiency greater than 40%, which is higher than advanced electrolysis models which attain efficiency of 30%[287].

The Net Zero Scenario requires low-emission heat in district heating systems to increase significantly, since fossil fuels currently supply account for significant portion of heat used in district heating. Most current nuclear reactor designs are already well adapted to supply district heating and even on a smaller scale using SMRs which can be used in localised district

heat production. Excess thermal energy from nuclear power plants can be injected into heating networks in a co-generation plant setup, which will significantly reduce the energy consumption used in heating[287].

Energy security concerns, more so with relation to Russia's invasion of Ukraine have shown the vulnerability of relying on fossil fuels especially Germany which abandoned nuclear energy for gas. lifetime extension of existing nuclear reactors has shown positive impact on nuclear energy especially cost while innovative financing mechanisms, like Regulated Asset Base model in the United Kingdom, have proved to be useful policy measures toward net Zero carbon emissions[304].

Between 2016-2020 annual investment in nuclear averaged over USD 35 billion per year spread across several regions. To be in line with Net Zero Scenario, investment in nuclear should be scaled upwards to over USD 100 billion in the late 2020s. This requires governments to reduce risks for nuclear power wherever possible[287]. The various measures and recommendations need are.

- i. Strengthen policy frameworks to reduce risks in investing in low-emission projects, like nuclear power plants. Since financing costs represent a large share of total costs of nuclear power, risk reduction will reduce final costs to consumers throughout energy transitions.
- ii. Support innovative technologies like the SMR projects and hydrogen production through direct measures like the essential R&D capabilities, talent, and the development of licensing frameworks.
- iii. There is need to review national and international decarbonisation pathways due to technological progress for nuclear power that include SMRs, and new applications in hard-to-abate energy sectors.
- iv. Facilitate efficient and effective safety regulations as well as appropriate waste management, and safety regulations for safe nuclear power generation. Regulators should skills and resources to review new projects and develop harmonised safety criteria for new designs. Licencing requirements should be clearly communicated to all parties.

- v. Accelerate the development and deployment of SMRs by identifying opportunities for SMR technologies to be cost effective investment and develop supply chains, to strengthen the SMR industries and promote earlier deployment.
- vi. Improve the supply chains and talent pipelines, building on any existing nuclear supply chains and cooperate with other industries relevant to the nuclear technologies like SMRs supply chains e.g., shipbuilding for modular construction.
- vii. Facilitate public engagement with all relevant stakeholders more so the local communities where nuclear technologies are expected to be deployed for acceptance[287]. .

Commercialisation for new nuclear technologies, and reduction in costs can be accelerated by international collaboration. This can be achieved by coordinating the developing new designs and construction of commercial-scale projects to avoid duplication and hence avoid unnecessary costs and slowing down of innovation. Regulation and approval of new designs can significantly benefit from international collaboration. Faster implementation and lower project management costs will be achieved by collective review and approval of designs which shortens the time to market and reduce the access costs. This will facilitate standardisation of processes for new products and technologies like the SMRs which can be built at factory and transported to operational sites[287].

Nuclear power plants produce intense heat used to generate steam to run a steam turbine connected to a generator that produces electricity. Nuclear power plants are used as base load stations. Nuclear reactors are classified as large, medium, and small-sized nuclear reactors. There is a growing trend for development of small sized reactors away large nuclear reactors which have become less attractive. Small-sized nuclear reactors were originally used to facilitate the development and demonstration of early reactor technologies to develop operational experience for the nuclear power sector. Basic of reactors is concerned with reliability, safety, and passive safety systems. A brief review of the design and safety aspects of some small nuclear reactors have been discussed. [1]

In nuclear power plants, water is heated to produce steam which in return is used to spin steam turbines that generate electricity. The heat used in nuclear power plants is produced during nuclear fission of radioactive materials in nuclear fuel. During nuclear fission, atoms are split

apart into subatomic particles releasing heat energy. The fission is controlled in the reactor of a nuclear power plant. Uranium fuel is contained in the reactor core of the power plants[504]. Nuclear energy is released by the nucleus, which is the core of atoms, made up of protons and neutrons nuclear energy can be produced by produced fission where the nuclei of atoms split into several parts or fusion in which the nuclei fuse together. The energy release is harnessed to generate electricity through nuclear fission, as fusion is still under research and development stage[300, 505].

5.21.1.Nuclear Reactors

Nuclear reactors and their equipment contain and control the radioactive chain reactions, of uranium-235, to generate heat. Heat produced heats the reactor's cooling agent, often water, to produce steam which is channelled the steam turbines, coupled to an electric generator for power generation [300]. The nuclear reactors contain and control the nuclear chain reactions to release heat at a controlled rate [504].

5.21.1.1. Boiling-Water Nuclear Reactors

In a boiling-water reactor, the reactor core heats water directly turning it to steam in the reactor vessel. The steam is then directed to the steam turbine generator for power generation. Figure 5-2 illustrates a boiling water reactor.

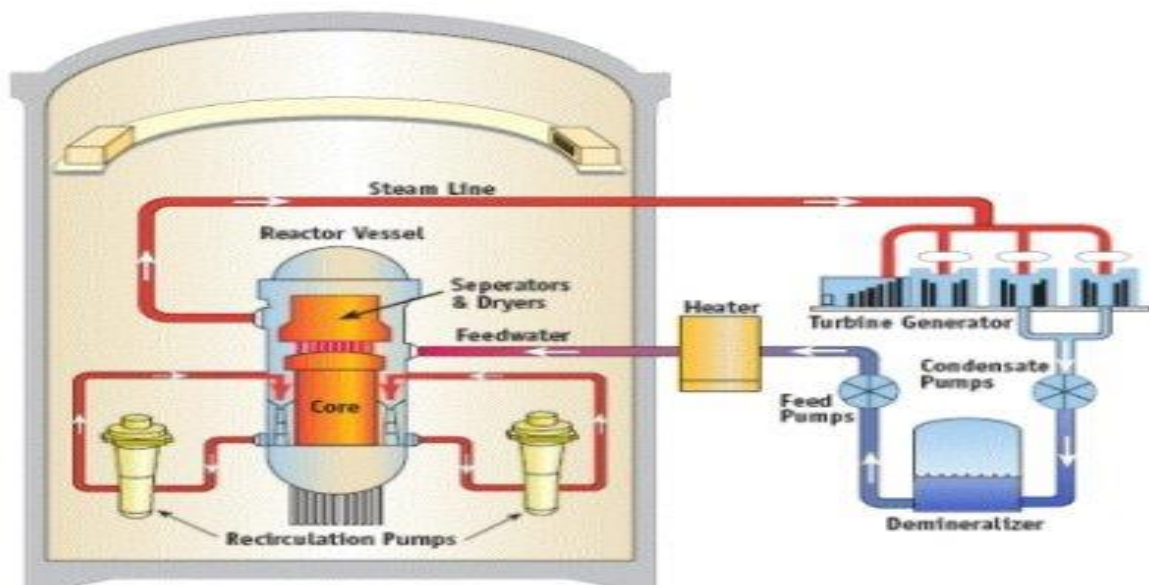


Figure 5-2: Diagram of a boiling-water nuclear reactor

Figure 5-2 shows a boiling water reactor in which water is in direct contact with the reactor core.

5.21.1.2. Pressurized-Water Nuclear Reactors.

In a pressurized-water reactor, the reactor core heats water under pressure in a closed loop which prevents steaming. The hot pressurised water flows through tubes in a steam generator. Which is a giant cylinder filled with clean water [504].

Source: U.S. Nuclear Regulatory Commission (public domain)

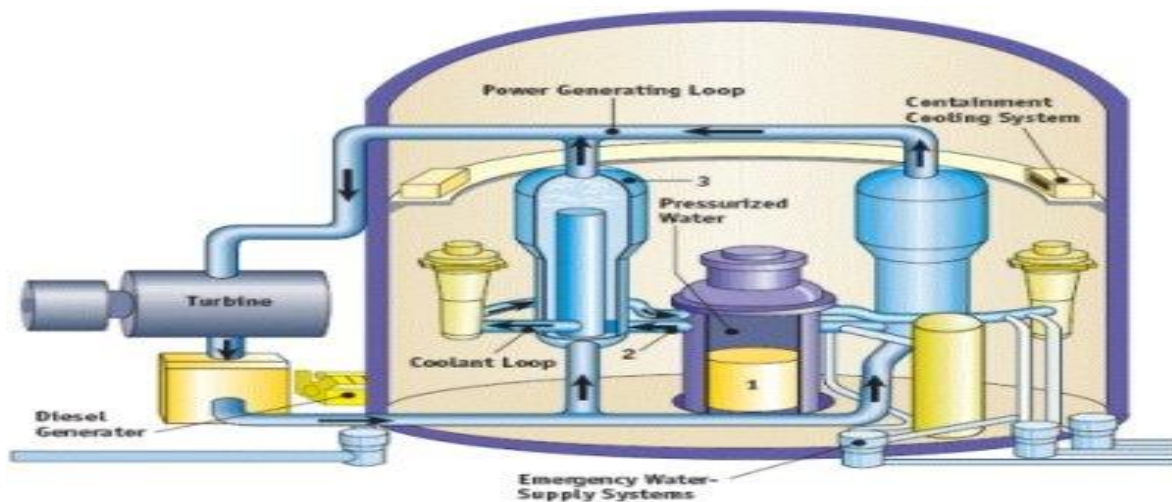


Figure 5-3: Diagram of a pressurized-water nuclear reactor

Figure 5-3 shows a pressurised water which has a coolant loop separate from the steam loop via a heat exchanger. The pressurised water is recirculated through the reactor core for reheating and once heated goes to the steam generator to boil clean water for more steam production. Out 92 nuclear power reactors in the United States as of July 1, 2022, 61 or 66% are pressurized-water reactors[504]. This demonstrates their popularity and wide use in power generation.

5.21.1.3. Small Modular Reactor (SMR)

The Small Modular Reactor (SMR) reactors that are smaller than conventional nuclear power plants which are generally above 1000 MW in capacity. The size and simplicity of the Small Modular Reactor (SMR) cut down time it takes to construct and commission a new nuclear power plant[300].

5.21.1.4. Other Reactors

Besides commercial nuclear power plants, there are about 220 research reactors in over 50 countries, with more being developed for use in research and training, manufacture of medical and industrial isotopes. Reactors for marine propulsion are generally confined to the major navies for the last five decades, for powering submarines and large surface vessels. Globally, over 160 ships, mainly submarines, are driven by 200 nuclear reactors with over 13,000 reactor years of experience in marine reactors. Many have also been decommissioned by Russia and the USA from the Cold War era fleet [505]

5.21.2.Sustainability of Nuclear Power Generation

The economic viability of a power plant is dependent on the cost of the electricity generated which is influenced by a wide range of factors and inputs from the inception to end of economic life. The Levelized cost of energy or electricity (LCOE) is a model used to estimate the cost of electricity before the powerplant is constructed. The cost of building a nuclear power plant and any financing cost is the most important contributing factor to the cost of from nuclear power plants. Although modern nuclear power plants are generally large and expensive, their long project lifetime effectively reduces the cost of nuclear power can still be relatively low. Nuclear energy has generally been regarded by public opinion as a harmful energy resource. The growing concerns over global climate change and greenhouse gas emissions have changed this belief and nuclear is now considered a reputable green power source that can generate significant amounts of energy with low carbon emissions. Nuclear energy is currently a mature low-GHG emission energy resource that is ideal for use as baseload power. However, the share in global electricity generation has been declining globally but its share of global electricity generation has been declining since the year 1993 because of various barriers and risks.

The life cycle GHG emissions from nuclear power are less than traditional fossil sources but assumptions and conditions under which they are deployed can have serious impact on the magnitude of life cycle GHG emissions compared to renewable technologies. The published median, interquartile range (IQR), and range for LWR life cycle GHG emission are 13, 23, and 220 grams of carbon dioxide equivalent per kilowatt-hour (g CO₂-eq/kWh), respectively. Upon application of harmonizing methods to use consistent gross system boundaries and

values important system parameters yielded 12, 17, and 110 g CO₂-eq/kWh, respectively. Based on ongoing improvements, median life cycle GHG emissions could be 9 to 110 g CO₂-eq/kWh by 2050

The levelized cost of energy (LCOE) for nuclear power plants in the is between \$97 per MWh and \$136 per MWh which is broadly similar to the cost of electricity from a coal-fired power plant without carbon capture and storage although it is more expensive than onshore wind power, utility solar power, or natural gas combined cycle. The cost does not however include the decommissioning [503]. The cost capital cost varies from country to country. According to the IEA analysis, it varies between \$40 per MWh in South Korea and \$101 per MWh in the United Kingdom and \$37 per MWh and \$48 per MWh two Chinese projects cited above at discount rate of 7% [503].

5.22. Geothermal Power Plants

The content of this section is published in the authors publications reference number [44, 58, 332, 347, 394, 502] The energy potential of geothermal resources is significant, compared to the energy needs of the entire world and so can play a leading role in global sustainable development Geothermal energy constitutes the natural internal heat of the earth found within rocks and fluids. The origin of most of the heat is most of geothermal heat is the natural decay of radioactive elements in the earth's crust.

Geothermal energy is a form of renewable energy with the ability to supply reliable electricity for base load demand electricity and heat supply. Therefore, they have a role to play in mitigation against greenhouse gas emissions through displacement of fossil fuel sources of energy in heat and electricity generation [506-509]. Geothermal energy potential is so huge with 99% of the planet earth being hotter than 1,000°C while 99% of the remaining 1% which has less than 1000°C has a temperature greater than 100°C [508]. Thermal energy stored in earth's crust has capacity to meet the entire energy needs of mankind today [510]. The most attractive features of geothermal powerplants is that they are highly reliable and operate at high load factor and high capacity factors, with system reliability averaging 95% as well as average load factor of more than 95 % [109, 410]. However, geothermal power plants contribute less than 1% of global electricity capacity and register very slow rate of capacity growth compared to other renewable energy sources[226, 407], for example,

between the year 2005 and 2020, average annual capacity growth was just 4.01%[109, 410]. High temperature and enthalpy geothermal resources can be used to generate electricity, but they require the extraction of the geothermal fluid from depths usually more than 3 km underneath the earth's crust. The conversion technology varies from steam field to steam field and for the case of wellhead power generation, it, may vary from well to another, based on well characteristics and application.

Upon successful drilling and testing of exploratory well, a decision must be made concerning the number of production wells to be drilled in a particular geothermal steam field to fully tap the available resource. For a vapor dominated geothermal system, production wells are drilled, tested, and connected to a common power plant through a network of insulated steam pipes to deliver steam to the powerplant. Generally, based on production well capacity, tens of geothermal wells may be connected to a line for a 50-55 megawatt unit, with additional one or two additional wells being left on standby[424]. Drilling wells is expensive and time consuming as wells are often drilled one or few at a time based on the number of drilling rigs [511]. This often leaves successfully drilled and tested geothermal wells idle while awaiting completion of other wells needed to sustain operations of a central power plant[226, 411]. This creates an opportunity for temporary wellhead powerplant development.

5.22.1. Geothermal Conversion Technologies

There are three classes of geothermal powerplants based on thermodynamic cycles and conversion technology. These are dry steam powerplants, flash powerplants and binary and hybrid or combination cycle power plants. The selection of the conversion technology is guided by the geothermal fluid conditions[412]. The conversion technologies adopted are common to both central powerplants and the wellhead power plants[109, 226, 412]. The geothermal resource fluid is divided into three major categories, high temperature resource if it is greater than 150°C medium between 90°C and 150°C and low temperature if the resource temperature is below 90°C[412]. Over 70% of global geothermal resources are in the form of low enthalpy geothermal fluid. These resources have temperature that is less than 150 °C hence the popularity of the organic Rankine cycles (ORC) systems as the ideal technology for conversion of the low-temperature geothermal energy to electricity[512, 513].

The technology selection is guided by the thermodynamic properties of the steam or geothermal fluid [514]. The thermodynamic properties of the resource, especially temperature influences the resource application and energy conversion technology. The conventional Rankine cycle steam turbines normally operate at a temperature above 180°C (350°F) while non-electrical applications can efficiently use geothermal resources with temperatures of 40°C to 180°C or (100°-350°F), based on specific application [192, 424]. The operational design of geothermal power plants is similar to fossil fuel and nuclear power plants which are based on the Rankine cycle except for the source of heat which is the geothermal fluid from earth delivered through production wells and a series of pipes[515, 516].

5.22.1.1. Dry Steam Plants

For high enthalpy geothermal fluid normally with temperatures above 200°C in saturated or dry state, the geothermal fluid is directly piped to a steam turbine via a strainer to generate electric power[517]. This conversion system converts steam coming directly from the reservoir and usually with temperatures between 220–245°C[423]. Dry steam geothermal plants are rare because dry steam geothermal resources with such favorable conditions are scarce. Such resources are found at Larderello in Italy, The Geysers (USA), Old Faithful geyser at Yellowstone National Park in Wyoming (USA) which is in a protected area hence not developed and very few other known places globally[109, 518, 519], Lake counties in northern California [421], and the Kamojas in Indonesia[109, 424, 520].

5.22.1.2. The Flash System

In a flash geothermal system, hot water, or wet steam is driven to the separator from the production well where it is flashed to steam at a lower pressure as the denser liquid settles in the flash tank base from where it is drawn out of the flash vessel under pressure normal to the injection well or other lower pressure and temperature thermal application, electricity generation or both before injection back to the reservoir. Pressure reduction to a level below vapor pressure of the fluid in the separator or flash vessel causes the geothermal fluid to flash or vaporizes, into dry steam which is directed to a steam turbine for power generation. The exhaust steam exiting the turbine is condensed and injected back to the reservoir [424]. The flash systems are equipped with a separator which causes pressure drop that causes steam to be separated from the water. Steam generated is directed to a steam turbine where it expands

and condenses. The condensate is collected with the brine exiting the separator and reinjected back into the reservoir[206, 517, 521]. Flash systems can further be classified into single-flash, double flash or even triple flash based on the flashing stages adopted. The multi-stage systems can generate 15% to 20% more power output than the single-stage flash cycle system from the same geothermal fluid thermodynamic properties[522]. The flash system remains the most appropriate system of power generation for liquid-dominated geothermal systems. The system capacities generally varied from 3 MW to 90 MW while the average capacity of 25.3 MW[523].

5.22.1.3. Binary Power Plants

Binary cycles are used to convert medium-low temperature geothermal resources to electric power, mainly as binary and Kalina cycles [524]. Binary cycles use two fluids in a closed loop cycle, one being the geothermal resource fluid and the other an organic fluid[109]. The geothermal fluid is passed through a heat exchanger where it transfers heat to a low temperature boiling fluid which acts as a working fluid[226]. The working fluid vaporizes and expands through a turbine which rotates and turns into a generator for power production. The working fluid is then condensed and recycled through the heat exchanger repeatedly. The geothermal fluid leaving the heat exchanger in a single pass is often reinjected back to the reservoir[424]. The organic Rankine cycle is identified as the best cycle for low temperature thermal energy sources[81, 525].

There are various types of binary cycles used in geothermal power plants based on the selected working fluid. They are mainly classified into Organic Rankine cycles which use refrigerants or organic fluid, Kalina and Goswami cycles which use ammonia mixtures[514]. In Organic Rankine Powerplants, the geothermal fluid heats up and pressurizes a low boiling temperature and pressure a secondary fluid like penta-fluoropropane and Isobutane which normally in a closed cycle and hence no mixing.

The binary cycle power plants are designed to operate with two fluid loops consisting of a geothermal fluid loop and a power cycle loop and are classified as either organic Rankine Cycle plants or Kalina plants based on the working fluid used.[430]. The binary cycle power plants are safer with confinement of the geothermal fluid and yield more power compared to

other cycles for the same geothermal fluid conditions and can be applied in both small and big geothermal power plants from few kW to 50-100 MW [526, 527].

i. Organic Rankine cycles

The Organic Rankine cycle involves heating of the working fluid to saturation condition and then superheated in the evaporator. The superheated fluid then expands through the turbine to produce mechanical power that turns a generator for power generation [528]. The heat source for organic Rankine cycle can be geothermal, solar, biomass, or waste heat. The cycle can be used for power generation and to improve efficiency of industrial waste heat recovery systems[522, 529]. A comparison between Kalina and cycles shows that the organic Rankine cycle is more cost effective for medium fluid temperatures generally between 90 and 150°C. the selection of a suitable organic working fluid is guided by the flammability, non-corrosiveness, toxicity, and environmental impact like the green gas potential[522]. A significant drawback of low temperature low temperature Organic Rankine Cycle is high energy consumption by the pump due to small vaporization enthalpy that needs more flow rate for compensation. Low-temperature sources, components like the pump may end up consuming up to 50% of power generated as a result of high brine flow rate to the boiler for compensation of low source temperature [511]. More advanced forms of the organic Rankine cycles include the organic flash or regenerative cycle and the supercritical cycles.

ii.) Kalina Cycle

The Kalina cycles use a mixture of 70% ammonia and 30% water as the working fluid. with higher efficiency and exergy potential compared to the Organic Rankine cycles [413]. The Kalina cycle is a modified Rankine cycle the uses a distillation separator and absorption recuperator. This cycle was invented by Alex Kalina in the 1980s. For low temperature geothermal resources, the Kalina cycle generates more power than the organic Rankine cycle by between 10-42%. For medium temperature fluids, the Organic Rankine Cycle is a better option as it about 3% less costs compared to the equivalent Kalina cycle[530, 531].

iii.) Organic flash cycle (OFC)/Regenerative cycles

An organic flash cycle (OFC) is a cycle that avoids the state of isothermal evaporation and two-phase expander in the cycle which significantly reduces the irreversibility that is encountered during the evaporation of the cycle working fluid [21]. The cycle involves

heating the working fluid to saturation and there after it is throttled. The resultant saturated vapor from the flash separator expands through a turbine hence doing some work and rotating it. For a basic organic flash cycle, the saturated working fluid from the separator and turbine exhaust account for the largest percentage of total heat input. To improve the performance of the system, the working fluid is preheated by heat recovered from the saturated liquid or the turbine exhaust [532].

In a regenerative cycle, portion of the vapor exiting from the middle stage of the turbine is led to a regenerative chamber while rest of the vapor is allowed to expand through the turbine to the exhaust before entering the system condenser for condensation. In the regeneration chamber, some portion of superheated vapor, used to improve efficiency and minimizes irreversibility [528].

Organic Flash Cycles (OFCs) can achieve a good temperature match between the two fluids to reduce the heat lost by the saturated liquid in the flash separator which reduces the cycle efficiency. Improvement in the thermodynamic performance can be realized by regeneration through recovery of more heat from the saturated liquid for preheating of the working fluid [524]. In regeneration, there is optimization of the evaporation and flash temperatures to achieve maximum net electric power generation. In a typical set up, geothermal fluid with temperatures between 120°C and 180 °C with 70°C as fluid reinjection temperature is used. In modified or advanced cycle based on the organic flash system, the optimal flash temperatures are lower than the basic organic flash cycle. These improved or advanced cycles are organic flash cycle with regenerator (ROFC), the organic flash cycle with regenerator and organic flash cycle with internal heat exchanger (ROFC + IHE) as well as the modified organic flash cycle (MOFC) are low compared with that of a basic organic flash cycle (BOFC) because of the limits of the preheat load and the pinch point which lead to a higher vapor mass flow rates[524, 533]. The net power output increases and the decreases in the evaporator exergy losses by ROFC, ROFC + IHE and MOFC compared with those of BOFC tend to decrease with increasing geothermal water inlet temperature. A modified organic flash cycle (MOFC) can yield up to 66.2% greater net power than the output from the basic organic flash cycle (BOFC) when used for geothermal fluid temperature of 120°C. The main challenge with the modified organic flash Rankine cycle (MOFC) is that it requires more evaporator area

of about 51–78%. However, to the advantage, it requires less condenser area by 13–42% to produce same power as the organic flash cycle [524].

The ORC cycles, unlike other cycles, have organic fluid in the turbine exhaust existing in vapor phase. There is a need to recycle some part of the heat content of steam exiting the turbine to improve overall performance. To achieve this an internal heat exchanger is installed soon after the turbine but before the condenser to develop an alternative ORC cycle. This type of cycle which is referred to as ORC with internal heat exchanger [528]

In the study by [532] involving the use of a double flash Organic flash cycle O(FC), a modified OFC, two-phase OFC and a 2-phase MOFC showed that modified OFC (MOFC) can generate up to 10–12% extra power compared to a conventional ORC.. A two-phase expander is used in the place of a high-pressure throttling valve to reduce throttling irreversibility in the two-phase OFC. A two-phase MOFC produced up to 20% more net power compared to an ordinary ORC[532]. In terms of thermodynamic efficiency and economics of OFC and regenerative cycles (OFRC), [533] established that the unit cost of the OFRC was reduced and the efficiency of a double-flash OFRC was better than that of conventional organic Rankine cycles [534].

iv.) Supercritical Organic Rankine Cycles

In a supercritical Organic Rankine cycle, the evaporation pressure should be made greater than the critical pressure of the working fluid to avoid the isothermal evaporation. This helps to improve the temperature matching between the working fluid and the heat source fluid. However, higher turbine inlet pressure causes an increase in pump power consumption, increases the investment cost, as well as operational safety requirements making the system more expensive. The use of a non-isothermal phase change of a zeotropic mixture allows for a good match of the temperature profiles in the process of evaporation and condensation. The main challenges of zeotropic mixtures are the uncertainty over the thermodynamic properties of the fluid which inhibits accuracy of computational models and efficient system design. Additionally, the heat transfer coefficients of zeotropic mixtures are lower hence require larger surface areas for adequate heat transfer. In a trilateral cycle, the liquid-phase working fluid absorbs heat from heating fluid in the cycle [35]. Use of this cycle leads to desired reduction in heat transfer irreversibility by adaptive temperature matching between the working fluid and

the heat heating fluid. However, the design of two-phase expanders with high isentropic efficiencies is still challenging[525].

5.22.1.4. Hybrid/Combined Cycles

These are integrated geothermal energy conversion systems i.e. combination plants or geothermal system in combination with at least one other different source of energy like solar, coal, etc. (hybrid plants) [535]. The overall objective in either arrangement is to achieve synergy and hence realize superior performance compared to separate or individual arrangement[535]. The benefits include higher utilization, higher thermal efficiency, increased net power output or more financial and economic benefits. Geothermal combined systems may consist of different types of flash-steam units and/or binary plants in an integrated combination that achieves advantages and benefits not realizable in separate units. Examples of hybrid systems include fossil-fueled plants, such as coal-fired central stations, gas turbines, biomass, or waste-to-energy plants, or concentrating solar thermal or photovoltaic plants working in conjunction with geothermal powerplant cycles like flash, binary or dry steam systems [535].

Combined cycles constitute a combination of two or more of the basic conversion cycles i.e., dry steam, flash, and the binary cycles[109]. The suitable combination is selected based on the steam temperature and pressure conditions, reservoir and fluid characteristics, investment cost, and application among others. Combinations include flash and binary, dry steam and binary, flash, and binary combined. Where a flash/binary hybrid plant is used, the fluid is first flushed to steam in a separator then steam is fed to the turbine as the separated liquid is directed to a binary cycle plant for extra power generation[421]. Other examples of combinations are single flash/binary, fossil/geothermal systems, etc. Any combination adopted should guarantee a higher efficiency, list cost and maximum power output [536, 537].

i.) Flash/Binary Combined Cycle

Depending upon of field characteristics, a geothermal powerplant design can be such that it starts with a flash cycle followed by a binary unit which uses waste geothermal fluid to as the heat source and a secondary fluid on the working cycle to generate extra power. This will form a combined or hybrid flash-binary plant. In the first cycle, a flash plant is operated by geothermal fluid from the production well which acts as the working fluid and is directed to reinjection well after exiting the turbine but with possible heat recovery before it goes back to

the reservoir[101, 538]. The waste leaving the separators can be sent directly to injection wells or can be sent to the binary station for heat recovery. This improves overall generation since extra electricity is generated from the same geothermal fluid[516, 536].

ii.) Solar-Geothermal Plant

A solar-thermal plant is a hybrid geothermal system where solar collectors are used to provide extra heat source to the organic Rankine geothermal system[539]. Solar energy is used to supplement the geothermal binary and geothermal flash-steam plants by means of superheating and/or preheating of the working fluid and hence supply more heat energy to the system. In the basic binary cycle plant, parabolic solar collectors are used to superheat the binary working fluid before it is directed to the turbine for power generation. The main challenge with the solar-thermal systems is the intermittence nature of solar energy supply or availability and hence necessary extra heating function[514-516].

Another system of solar-geothermal plant is a more complex flash-binary combination plant with solar-brine heating, a moderate-temperature geothermal brine is heated with solar energy to the design flash temperature. The flash steam is then directed to a topping up back pressure steam turbine for power generation. From the back-pressure steam turbine, which is the first turbine in the setup, the exhaust is directed to the condenser/preheater (C/PH) before being reinjected back to the reservoir. The hot-separated brine exiting the flash separator is then used to heat up the already preheated binary working fluid before the waste water or brine is mixed with the condensate before the mixture of the two is reinjected to the reservoir[515, 516].

iii.) Fossil-Geothermal Powerplants

It is possible to develop a combination of fossil fuel powerplant and geothermal energy source for electric power generation[512]. This combination of geothermal energy and fossil fuels for power generation offers many thermodynamic advantages compared to individual technology approach where the powerplants operate as standalone plants. Different approaches that can be used include fossil superheating of geothermal steam, use of geothermal heat in preheating of fossil fuel powerplants feed water which then replaces some high grade steam which can be used for extra power generation[512, 513], and development of a compound geothermal fossil power plants[512].

iv.) Combined Heat and Power/Cogeneration Cycles

Combined heat and power are simultaneous generation of electricity with heat or thermal applications which significantly improves the cycle efficiency[81, 107]. Use of cogeneration systems leads to higher thermodynamic and environmental performance and reduction in unit cost of energy[529]. CHP is increasingly used in geothermal energy exploitation as well as other renewable sources of energy like solar, wind and biomass. With huge quantities of low-grade heat in geothermal fluid, cogeneration has a special role in geothermal energy utilization [107, 540].

Co-generation systems are classified into topping and bottoming systems based on the sequence of energy exploitation adopted[107, 541]. In topping cycles, the energy supplied is first used for power generation followed by heat energy application, hence heat is a by-product of the cycle. Topping cycle is the most ideal for geothermal energy[542]. For a bottoming cycle, the energy is first used in thermal processes while rejected heat is used in power generation. These cycle are ideal in manufacturing like cement, iron and steel, ceramic production , gas production and petrochemical industries[516, 542].

Therefore, there are various conversion technologies available for use in geothermal electricity generation applicable to both wellhead and conventional power plants. Selection of conversion technology should balance between efficiency, exergy, and cost optimization to ensure optimum geothermal resource exploitation. The factors considered in technology selection are efficiency, financial and economic factors and geothermal resource and reservoir characteristics.

5.23. Hydro Power Plants

The power in moving water in streams and rivers has been used by man to produce mechanical energy for various applications. As a leading renewable energy source, hydropower was one of the first energy sources for power generation. Hydroelectricity generation varies annually, seasonally, and geographically [431]. Hydropower is a renewable energy source where electrical energy is derived from the potential energy of water moving from high to lower elevation. Hydropower is a mature technology and widely used; in 2016, a total of 159 countries in the world reported to have developed hydropower. Hydropower is among the most efficient technologies for production of renewable electrical energy, with a typical efficiency of 90% or better for, “water-to-wire.” Hydropower is cost competitive, and is today

the only renewable technology that can produce electricity at equal or lower cost, compared to thermal energy sources like coal, oil, or gas, typically in the range of $\text{US}2\text{--}5 \text{ c (kWh)}^{-1}$ (2–5 US cents per kilowatt hour)[301].

Adding to its contribution to energy generation, hydropower has a vital role in supporting grid stability, security of supply, energy storage, and balancing unregulated generation from other renewables like wind and solar power. In addition to energy and grid services, hydro reservoirs can deliver other important services such as water supply, irrigation, flood control, navigation, and recreation. Environmental and social concerns, unless carefully managed, represent challenges for further deployment of hydropower[543].

The first known hydropower plant (HPP) was installed in a house in Cragside, Rothbury, England, in 1870. Industrial use of hydropower started in 1880 in Grand Rapids, Michigan, when a dynamo driven by a water turbine was used to provide lighting. A breakthrough came when an electric generator was coupled to the water turbine and created the world's first hydroelectric power station (of 12.5-kW capacity) which was commissioned on September 30, 1882, on Fox River at the Vulcan Street Plant, Appleton, Wisconsin, United States, lighting two paper mills and a residence [1]. Early hydropower plants were much more reliable and efficient than the fossil-fuel-fired power plants, resulting in a proliferation of small- to medium-sized hydropower stations distributed wherever there was an adequate supply of water and a need for electricity. By 1886, there were 45 hydroelectric power plants in operation in United States. Many other countries followed suit, such as Norway, where the first hydropower plant began operation in 1885 in the town Skien. Only a few years later, in 1890, the town of Hammerfest, north of the Arctic circle in Norway, had electric streetlights supplied from a municipal hydropower system. By the end of the century, 14 towns in Norway had electricity supplied from hydropower[543].

5.23.1. Water Cycle

Hydropower is well understood by understanding the water cycle which has three steps:

- i. Water is heated and evaporated by solar heating of water on the surface of rivers, lakes, and oceans, which causes evaporation.
- ii. Evaporated water vapor condenses to form clouds and falls as precipitation in form of rain and snow.

- iii. The precipitation accumulated to form streams and rivers, which drain into oceans and lakes, from where it evaporates and begins the cycle again.

The amount of precipitation that drains into rivers and streams determines the amount of water for hydropower generation. Availability of hydropower is significantly affected by seasonal variations in precipitation and changes of weather patterns like droughts, which affects availability of hydropower production[431]. Hydroelectric power generated is influenced by the amount of water. Since hydroelectric power is derived from water, hydroelectric power plants are located on or near a water source. Available energy is determined by the volume of the water flow and the water head. The greater the water flow and the higher the head, the more electricity the power plant can produce.

The water cycle influences the amount of precipitation in a place and hence the quantity of water available to flow in the rivers and storage facilities. Figure 5.4 shows the water cycle.

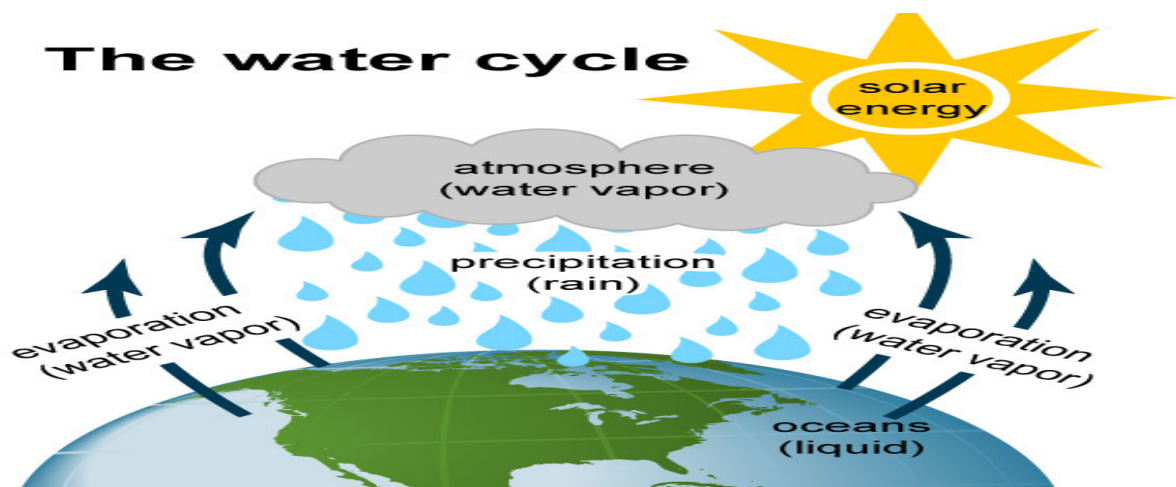


Figure 5-4: Hydrological cycle

From Figure 5-4, it is noted that the sun heats the water surfaces causing evaporation of moisture to the atmosphere and from the plants and other surfaces with water. The vapor cools in the atmosphere to form clouds and come back on the earth's surface as precipitation. Part of the precipitation is absorbed by plants from the soil, why surface and underground flow finds itself in springs, rivers and surface water bodies to start another cycle as the sun heats water plants.

5.23.2.Hydropower Generation

In the hydropower plants, water flows through a pipe, or *penstock*, to the turbine to rotate the blades in a turbine that spin to power a generator for electricity generation. The main types of conventional power plants include runoff, river power plants and storage systems, and the pumped storage power plants.

i. Run-of-the-River Systems,

In these systems, the force of river's current applies pressure on a turbine which rotates the turbine generator. These facilities can be equipped with a *weir* in the water course which diverts water to the hydro turbines.

ii. Storage Systems,

Hydropower plants with storage involve accumulation of reservoirs created by dams on streams and rivers for controlled release through the hydro turbines.

iii. Pumped-Storage Hydropower Facilities

This is a type of hydroelectric storage system in which water is pumped from a water source up to a storage reservoir located at a higher elevation for release through a turbine to produce power. Water pumping to the upstream storage is usually done when electricity demand and generation are low for release to generate electricity during peak electricity demand periods when prices and demand is high. Pumped-storage hydroelectric systems consume more electricity to pump water to the upper water storage reservoirs than they generate with the stored water and therefore have net negative electricity generation balances but they take advantage of price differences to operate economically and profitably [431]

5.23.3.Sustainability of Hydropower Generation

The technical potential for hydropower worldwide is between 31 petawatt-hours a year (PWh/y) to 127 PWh/y, while the economic potential is between 9 PWh/y to 15 PWh/y, the report notes. Hydropower, which is the dominant component of renewable energy, is also under the threat of climate change. Climate change has a large impact on water resources and thus on hydropower. Hydropower generation is closely linked to the regional hydrological conditions of a watershed and reacts sensitively to seasonal changes in water quantity. Hydropower is one of the oldest sources of mechanical power and the largest source of renewable electricity generation in use. Global capacity is around 1300 GW. Hydropower is

site-specific and so each project will be unique. Hydropower plants are classified according to their size into micro, mini, small, and large hydropower. In terms of generating the capacity the large plants are the most important. These can be either dam and reservoir plants or run-of-river stations. The latter are the easiest to construct and least disruptive, but the former stores energy and is therefore much more flexible in the way it can be used. Energy is taken from hydropower plants through turbines and a number of designs such as Pelton, Francis and Propeller turbine exist to exploit different head heights of water. Most hydropower developments have environmental effects which must be taken into account before construction. Hydropower potential is a function of available water and suitable terrain

The main advantages of hydropower are low unit cost, low emissions, ease of control and storage. The challenges of hydropower are huge land requirements for storage, soil erosion, ecosystem disturbance and seasonal variability. About 75,000 hectares of land and 14 trillion liters of water are required on average basis to produce 1 billion kWh annually. Hydropower plants have a reservoir developed behind a dam to supply water to the hydraulic turbine for generation of a highly flexible, dispatchable electricity supply. Hydropower can be combined with wind, solar and other sources to supply reliable steady and affordable grid electricity. Hydropower can also be exploited from run-of-the-river resources which have less environmental impact but with overreliance on steady supply of rainwater whose supply is unsteady and unpredictable. Apart from power generation, reservoirs can control floods, supply water, and power from stored water even during drought. Hydroelectric electric power plants are useful for grid electricity sustainability particularly during peak hours where plants that generate flexible and cheaper electricity are on high demand.

5.24. Biomass Power Plants

A biomass power plants generate electricity from the steam produced by combustion of plant or animal matter in a combustion chamber[302]. Important processes in biomass power production are.

- i. Combustion is an oxidation of the biomass to produce heat and flue gases.
- ii. Heat produced heats water in the boiler and transforms it to steam which is directed to steam turbines coupled to generators.

- iii. Electricity production by the turning of turbogenerator which may be stepped up and transmitted to the grid.
- iv. Condensate/waste heat recovery
- v. At the turbine exhaust, part or all the used steam is condensed and recovered and fed back to the boiler.

In cogeneration setups, part of the steam or all is extracted as exhaust steam or extracted steam from between the turbines stages and used for process applications like heating. Cogeneration significantly increases the cycle thermal efficiency of the biomass power plants. [302]. A typical case of cogeneration is the use of bagasse by sugar mills to generate both electricity and for process heating[57, 64, 296, 495]..

5.24.1.Design and Construction of Biomass Power Plants

The main features of a biomass power plant are the chimney, the boiler, the furnace, ash handling system and fuel storage and handling systems. A solid biomass plant is demonstrated in Figure 5-5.



Figure 5-5: A solid biomass power plant

Figure 5-5 shows the construction of a biomass power plant with main features. The Power plants maybe designed to handle multifuel sources.

5.24.2. Advantages of Biomass Power

The main advantage of biomass power plants is that they exploit well established and mature technologies to produce electricity without using fossil fuels, using technically similar technologies and equipment. [302].

5.24.3. Pathways for Biomass Energy Generation

5.24.3.1. Combustion of Raw Material

Biomass combustion is the most frequently adopted method to burn biomass, often wood in boiler furnaces e.g. bagasse combustion in sugar cane factory boilers[302].

5.24.3.2. Gasification:

Gasification is a high temperature thermochemical process, used to transform solid biomass into combustible that can be used in many ways. Biomass raw material is transformed into a gas. The gasification process takes place between 800°C and 1400°C that with feedstock being dry biomass, solid recovered fuels, or wood waste. [302].

5.24.3.3. Methanization:

Methanization does not involve fermentation of the organic materials used, such as household waste, paper, cardboard, or manure, instead of direct combustion. The process produces biogas which can then be used as a combustion fuel. [302].

5.25. Wind Power Plants

Wind power generation developers examining power plants on a 20-year investment span posit that natural gas prices are the main driver of wind power generation making the investment profitable and competitive if price of natural increases. The growth of wind power generation investment is driven by tax incentives, demand, reducing costs, and better or improved technology, which include taller towers and lighter rotor blades.[544]. Other important factors in modelling wind power generation are subsidies like the production tax credit (PTC), depreciation, and taxes.[544].

Transmission costs remain a major issue in wind energy development because some of the best locations for wind power generation are far from the consuming load centres. Upgrade of transmission lines through electrical power grid using high-voltage DC instead of high-voltage

AC is preferred to tap those distant sources. For areas where water supplies are abundant, like along seashores or internal lakes or rivers, wind power generated can be used to produce hydrogen from water by electrolysis process, stored and transported energy carrier of wind energy. Hydrogen can be conveyed or transmitted to load centres possibly through natural gas pipeline infrastructure. Alternatively, the hydrogen can be used to produce methane gas, CH₄ from coal and distributed through the existing natural gas distribution grid with little modifications, while methane itself may be converted into methanol or methyl alcohol, CH₃OH as a liquid fuel for transportation. Transmission losses may be reduced by use of superconducting electrical transmission lines cooled with cryogenic hydrogen carrying simultaneously electricity and hydrogen power plants to load centres. With such visionary futuristic power transmission system, power can be availed for a modern mass transit system using magnetically levitated (Maglev) high-speed trains transporting goods and people supplementing the current highway system [544].

5.25.1.Sustainability of Wind Power Generation

5.25.1.1. Technical Sustainability

Modern wind turbines capture the kinetic energy of moving air and convert it into shaft power to drive an electrical generator/alternator. The turbine is typically comprised of three basic parts: the rotor, the nacelle, and the tower. The rotor includes the turbine's blades (most often 3 in horizontal wind axis turbines) and the nose cone/hub. The nacelle contains the driveshaft, transmission a, the unit's generator/alternator, the electronic controls to convert the generators or alternator's electrical output to quality suitable for use, and the tail vane or yaw drive that keeps the turbine oriented to the wind, either upwind or downwind depending on the turbine's design. Because wind speed generally increases and turbulence decreases with height, a tower helps the system increase its energy production and reduces turbulence-induced mechanical stresses, thus enhancing its economic benefit.

The ability of a turbine to produce energy from the wind fundamentally depends on the wind resource and the swept area of the turbine. Simplifying somewhat, the power output of a turbine is proportional to the cube of the wind velocity and the square of the blade length. A doubling of the wind speed thus yields an eight-fold increase in wind power while a doubling of a turbine's blade length yields a four-fold increase in energy capture (all other things kept

constant). Larger turbines with longer blades not only produce more energy for a given wind resource, but they are also more capital cost-effective as well, because of inherent economies of scale as well as inefficiencies in the market for smaller turbines. The installed cost/kW for a small turbine is twice that for a mid-scale turbine and can be several times as expensive as that for a utility-scale turbine. While these factors argue for choosing the windiest sites and installing the largest turbines on the highest towers that are cost-effective for the site – an argument understood by wind farm developers – residential and commercial site hosts cannot follow this logic to its conclusion. It is a rare home or business owner that is going to move their establishment simply to take advantage of a windier site. And several practical constraints prevent home and business owners from using the giant turbines typically found in utility-scale wind farms. Neighbors might object to the presence of a turbine hundreds of feet tall because of safety, noise, and visual concerns.

The turbine's capital costs are an additional consideration: even if a site host has the space for a giant turbine, the multi-million-dollar capital cost can be difficult to finance for someone not in the wind industry. As a result of these constraints, most distributed wind turbine installations are sized roughly equivalent to the site host's electrical load and use turbines much smaller than those found in current-day wind farms. This analysis therefore assumes that residential customers will install turbines with nominal capacity ratings of 1-9 kW, while commercial customers will install turbines with nominal capacity ratings of 10-100 kW

5.25.1.2. Levelized Cost of Wind Power Generation.

The levelized cost of electricity (LCOE) for wind power is such that fuel cost is zero in wind power generation, and while wind turbines are usually factory-assembled and directly delivered to site, leading to shorter construction time, t . The LCOE for wind power generation is usually estimated over the lifetime of the energy-generating technology, usually 20 years at a discount rate (i) which depends on the cost and the source of the available capital, while considering a balance between equity and debt financing and an estimate of the financial risks for the project[544].

Initial capital cost (ICC) and capacity factor are important drivers of the LCOE for wind power plants, but discount rate and annual operating expenses (AOE) are non-trivial[363]. Examples of the Wind LCOE are demonstrated in Figure 5-6.

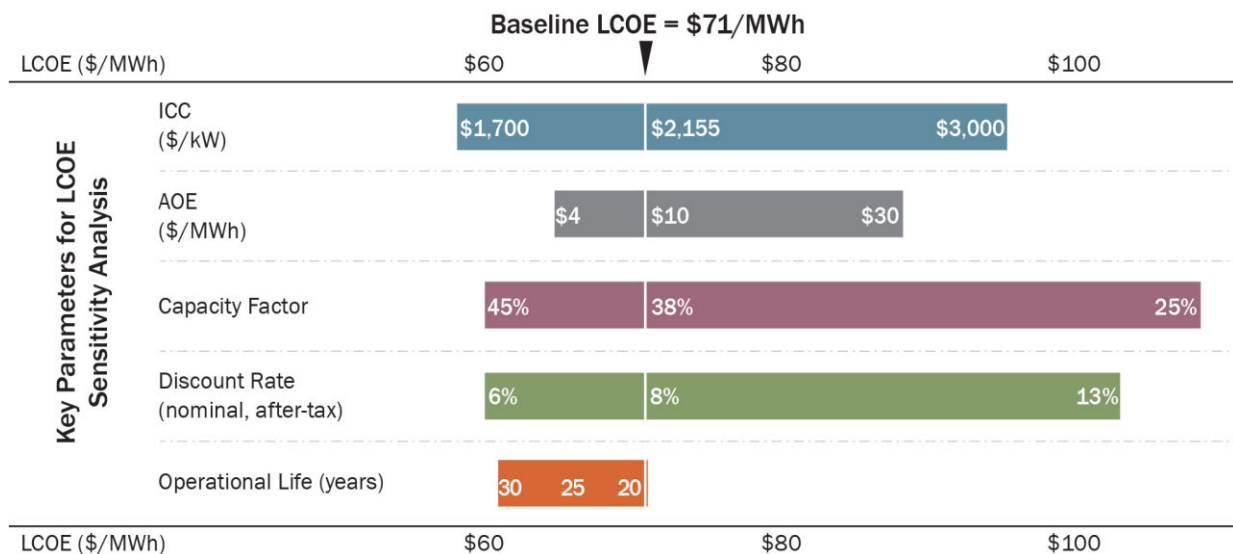


Figure 5-6: Levelized cost of Wind power generation.

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5.26. Solar Power Generation

Solar power generation involves converting energy from the sun into electricity. Heat and electricity are the two forms of energy generated from the sun use. Energy is generated by means of solar panels, which vary in size from residential rooftops to 'solar farms' spread over large land space. The global commitment to reduce greenhouse gas emissions while achieving significant cost reductions, have generated demand for solar electricity making it one of the fastest growing renewable energy resources. The global solar power deployment increased from 40 GW in the year 2010 to 586 GW in the year 2019[545].

Power fluctuations cover short and mid-term power variations in a timescale from seconds to hours. Intermittency is deemed to cover long-term power variations in the timescale from hours and days to years. Intermittence for solar energy is considered more challenging than power fluctuations. It is the deterministic astronomical diurnal and seasonal cycles, and the optical transmissivity of clouds and aerosols following atmospheric circulation patterns that determine the solar radiation reaching the Earth's surface. For this reason, the intermittency of

solar power is in timescale of hours up to months because of diurnal and seasonal cycles, and this adversely affect the reliability and stability of power grids. In Great Britain (GB) energy the cost of backup capacity for solar is expected to increase from £2.5/MWh in 2016 to about £4.5/MWh by 2030, implying that high penetration of solar requires more backup procured through the capacity market and will increase capacity payments to incentivize entry as the while higher levels of solar lowers daytime power prices. Measures to accommodate high photovoltaic (PV) penetration, include proactive curtailment, energy storage and demand response to take advantage of the spatial diversity by spreading PV farms over a large geographical area[545]

5.26.1. Photovoltaic Power Generation

An individual PV cell can generate a voltage ranging between 0.5 – 0.6 V on no-load (open circuit) when exposed to solar but drops to about 0.46 V as soon as it is loaded (connected to an electric circuit). The current produced depends on its size, hence the greater the area exposed to sunlight, the greater the output current since it is exposed to more sunlight (insolation), A PV cell can deliver 3-5 A in current when exposed to an area of 100 mm × 100 mm depending on the level of insolation[433]. The role of solar in many grids remains minimal, for example in the 2017/2018 financial year, about 3% of Eskom's generation capacity was derived from independently operated PV solar farms.

A PV array consists of many individual cells connected in series to increase the voltage output voltage, while strings of cells are connected in parallel to increase the current output to the desirable level. The output of a solar arrays in a solar farm, s is sent to an inverter, for conversion from dc to ac at power frequency (50 Hz) for step up and transmission to the grid. The application of the solar energy influences the actual physical dimensions of a solar array, with grid connected systems being extremely large with many tens of thousands of individual PV cells.

5.26.2. Advantages

The advantages of PV electricity generation in a large solar energy farm are significant[433].

- i. Solar energy is renewable and cannot be depleted in generation of electricity, there is no depletion of a natural energy source, it is renewable energy, although manufacture of parts has negative impact to the environment. [433]
- ii. Many parts of the solar PV power system can be recycled or disposed of, without environmental contamination.
- iii. The cost of solar PV cells has significantly reduced over time the rate of ageing to end-of-life is also reducing, hence a longer functional life of solar arrays.
- iv. The modular nature of installations in a solar farm implies that a portion of the plant can be taken out for maintenance without interfering with the entire generation.
- v. The current solar PV technology is reliable, and suppliers of PV arrays can guarantee above 80% of its rated value for 25 years of operation. The recommendation is that the PV cells should be replaced after this time.

5.26.3.Limitations of Solar electricity

- i. Significant quantity of energy and emissions are associated with the production of PV cells generating environmental impacts.
- ii. The initial cost of solar power plants is relatively high.
- iii. The intermittence of generation requires storage which increases the cost of the installation.

5.26.4.Concentrated Solar Energy

The concentrated solar technology makes use of sun-tracking reflectors (mirrors), called heliostats, that are used to focus the sun's radiation onto the receiver which is filled with a heat transfer fluid, that can absorb and be heated up by the sun's radiation for transmission to a heat exchanger where it is used to generate steam, which is then applied to drive a steam turbine and generator for power generation.

Two technologies are important. Are the parabolic trough and the power tower.

5.26.4.1. Parabolic Trough

The heliostat is a long trough with a parabolic reflecting surface profile while the receiver is a metallic pipe mounted at the focal point of the parabolic reflector and running the length of the

trough. The receiver is exposed to the energy collected by the entire hyperbolic trough. A heat transfer fluid is pumped through the receiver to the heat-exchanger steam is generated for use in driving a steam turbine for power generation [433]. Figure 5-7 shows a parabolic reflector.

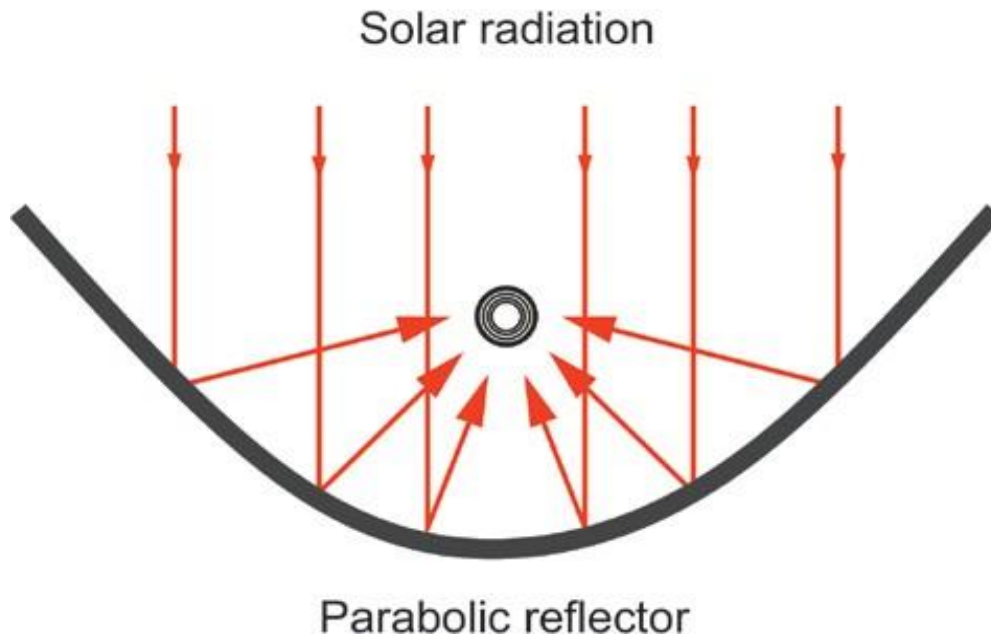


Figure 5-7: The parabolic reflector used for concentrated heating of a pipe filled with water.

Figure 5-7 shows the general construction of a parabolic reflector.

5.26.4.2. Power Tower (Concentrated Solar Plant)

Power tower technology applies an extensive field of heliostats to reflect the sunlight onto a receiver which is mounted on a central tower in the middle of the field of mirrors for concentration of the sun's rays to raise the temperature of the heat transfer fluid in the receiver. The heat transfer fluid is pumped to a heat exchanger for steam generation [433]. Some of the heat transfer fluid is diverted to a thermally insulated storage vessel, used for generation when the insolation level drops and generation is reduced[433]. Figure 5-8 illustrates a solar power tower plant.

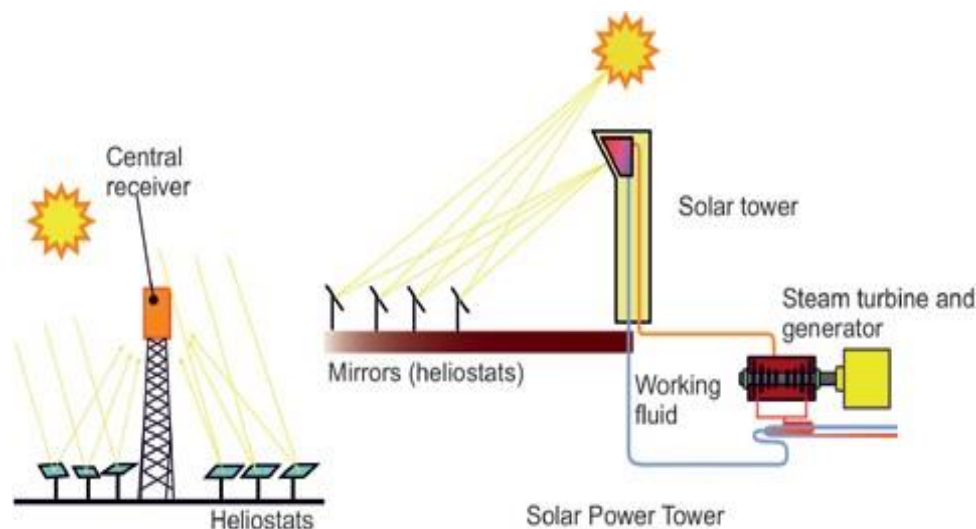


Figure 5-8: Power Tower (Concentrated Solar Plant)

Figure 5-8 illustrates the principle of using an extensive field of heliostats to focus solar radiation on a receiver, at the top of a tower, for concentrated heating.

The heat transfer fluid generally a mixture of sodium nitrate (NaNO_3) and potassium nitrate (KNO_3). mixed in the ration 60:40 whose operating temperature range is $260^\circ\text{C} - 550^\circ\text{C}$. Care The salt mixture should not solidify to protect the pipework from damage when it thaws. This can be achieved by use of heat-storage and circulation when the insolation levels are low. For the financial year 2018/2019 ‘Concentrating Solar Power’ supplied some 300 MW of generating capacity of Eskom [433].

5.27. Ocean Thermal Generation

Ocean thermal energy conversion (OTEC) harnesses the temperature differences (thermal gradients) between ocean surface waters and deep ocean waters caused by heating of ocean surface water by the sun. Tropical regions generally have surface water being warmer than deep water. The thermal gradient can be used to generate electricity and to desalinate ocean water. Ocean Thermal Energy Conversion (OTEC) systems work with thermal gradients of at least 20°C (or 36°F) to power a turbine to generate electricity. The warm surface water is pumped through an evaporator that has a working fluid that vaporizes to drive a turbine/generator. The vaporized fluid is condensed using cooling water from deeper in the

ocean. OTEC systems that use seawater as the working fluid can apply the condensed water to make desalinated water[546]. Figure 5-9 illustrates an ocean thermal power plant.

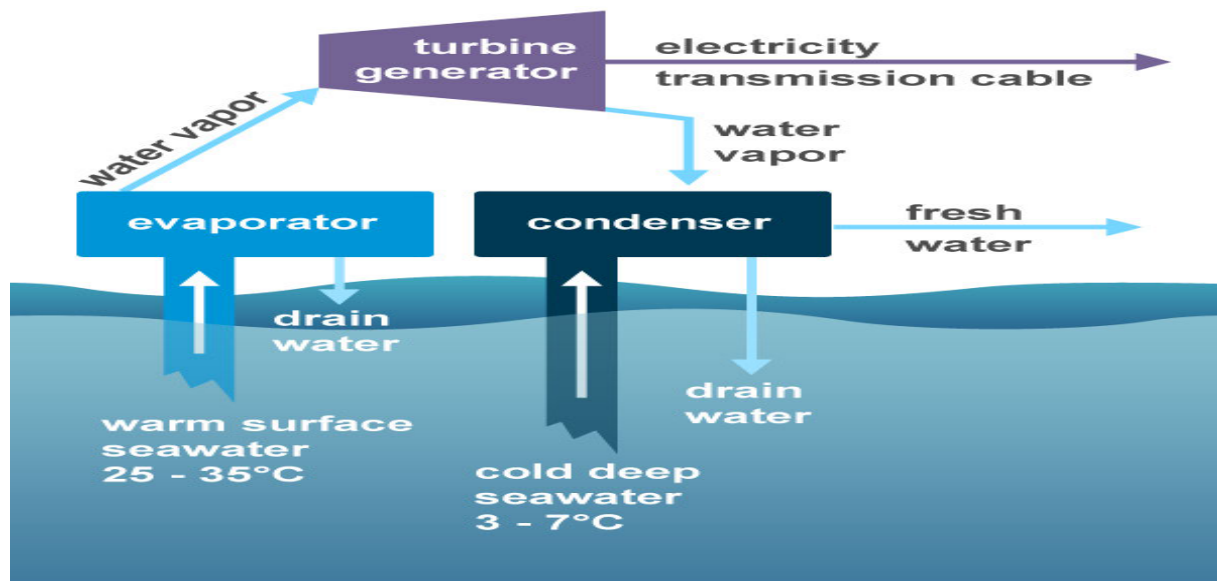


Figure 5-9: An Ocean thermal generation[546]

From Figure 5-9, it is observed that the main elements of an ocean thermal power plant are the evaporator, the turbine generator, the condenser electricity transmission cable.

The US started TEC research in 1974 by establishing the Natural Energy Laboratory of Hawaii Authority which is one of the world's leading test facilities for OTEC technology and operated a 250-kilowatt (kW) demonstration OTEC plant for six years in the 1990s. The US Navy developed a 105-kW demonstration OTEC plant at the laboratory site which started operations in 2015 supplying power to the local electricity grid[546]. Other larger OTEC systems are under development and demonstration in several countries and they mainly supply power and desalinated water [546].

5.28. Wave Power Generation

Waves are generated as the wind blows over the surface of open water in lakes and oceans. Waves have significant energy potential. the theoretical annual energy potential of waves off the US coasts is about 2.64 trillion kilowatt-hours, which is about 64% of total U.S. utility-scale electricity generation for the year 2021. Potential sites for wave energy exploitation are found along the coasts Europe, USA coasts and the coasts of Japan and New Zealand. There are

different technologies for capturing and converting wave energy to electricity. The technologies include placing devices on or just below the surface of the water and anchoring devices to the ocean floor[305].

Wave energy can be harnessed by bending or focusing waves into a narrow channel to which increases their size and power to rotate turbines for power generation. A catch basin or reservoir can also be used where the water flows to a turbine at a lower elevation, just like the way a hydropower dam operates[305]. Figure 5-10 shows the construction of a typical wave site.

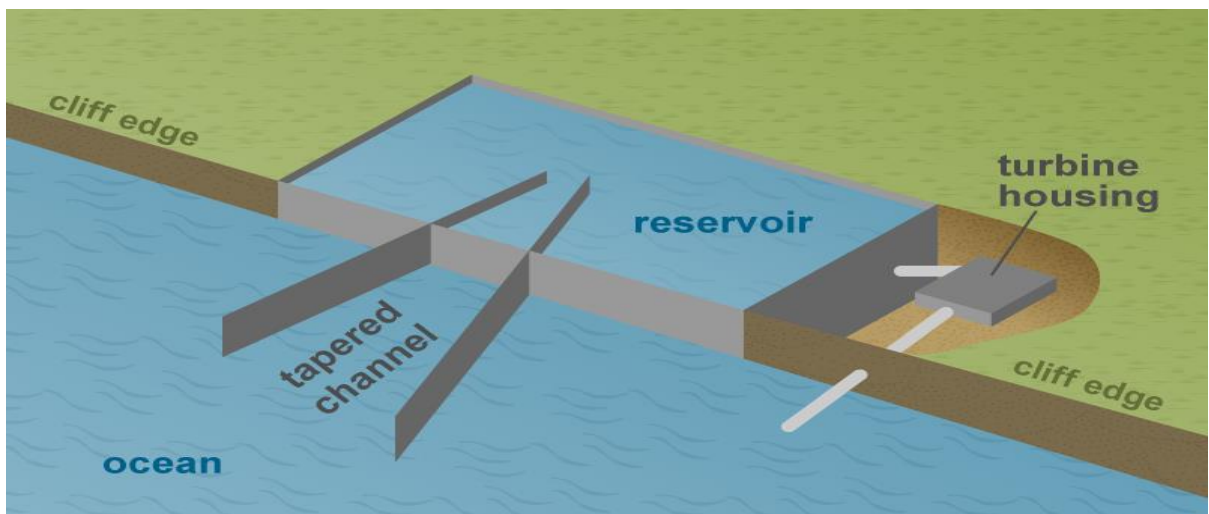


Figure 5-10: Wave energy site

From Figure 5-10, it is noted that the main features of a wave power are the cliff edge, tapered channel, reservoir, turbine, and turbine housing.

5.29. Tidal power

Ocean tides are created by the gravitational pull of the moon and sun together with the rotation of the earth. Tides can cause water levels near the shore to rise and fall up to 40 feet. Tides were used in Europe to operate grain mills over 1,000 years ago, and today, tidal energy systems produce electricity. Economic generation of tidal energy needs tidal range of at least 10 feet. [547]

5.29.1.Tidal Barrages

A tidal barrage or dam is a structure like a dam installed across an inlet of an ocean bay or lagoon to form a tidal basin. The water levels and flow rates are controlled by sluice gates located on the barrage to allow the tidal basin to fill on the incoming high tides and to empty through an electricity turbine system on the outgoing ebb tide. A two-way tidal power system produces power from both the incoming and outgoing ocean water tides[547]. A tidal barrage can change the tidal level in the basin and also increase of water and can affect navigation and recreation[547].

Examples of tidal power barrages include the Sihwa Lake Tidal Power Station in South Korea with power generation capacity at 254 megawatts (MW) and La Rance, in France, which is the second-largest operating tidal power plant with capacity of 240 MW generation capacity. Annapolis Royal in Nova Scotia, Canada, having generation capacity of 20 MW of electricity is another large tidal power plant [547]. Figure 5-11 illustrates a tidal power plant.



Figure 5-11: Barrage of the tidal power plant on the estuary of the Rance River in Bretagne, France

From Figure 5-11, it is noted that a tidal power plant features include mounting structure and water flow features.

5.29.2.Tidal Turbines

The Tidal turbines are like wind turbines since they have blades which rotate a rotor for power generation. Tidal turbines may be placed on the floor of the sea floor which has strong tidal

flows. Since the water is about 800 times denser than air, tidal turbines should be made much sturdier and heavier than compared to wind turbines. This makes tidal turbines are more expensive compared to wind turbines. However, given same size of tidal turbines and wind turbines, the tidal turbines can capture more energy [547].

5.29.3.Tidal Fences

A tidal fence refers to a typical type of tidal power system having a vertical axis turbines mounted in a fence or row placed on the seabed, which is like tidal turbines. As water passes through the turbines, rotating them, a generator mounted on the shaft generates electricity [547].

5.30. Magnetohydrodynamic Power Generation

The word magnetohydrodynamic is derived from *magneto-* which means magnetic field, and *hydro-* meaning liquid, and *-dynamic* which means movement. MHD field was initiated by Hannes Alfvén, who received the Nobel Prize in physics in 1970. The concept MHD is that magnetic fields can induce electric currents in a moving conductive fluid, which in turn creates forces on the fluid and changes the magnetic field itself. The equations applied in the description of MHD constitute a combination of the Navier–Stokes equations of fluid dynamics and Maxwell’s equations of electromagnetism which must be solved simultaneously, by analytically or numerical techniques[298].

Magnetohydrodynamics (MHD) is the study of the flow of electrically conducting fluids in the presence of magnetic fields. The applications of MHD covers many physical objects, from liquid metals to cosmic plasmas. The mathematical model of MHD, it is based on the equations governing fluid motion in a magnetic field and the equations governing electromagnetic fields in moving fluids. MHD is a coupled system where the Navier–Stokes equations are coupled with the Maxwell equations through the Lorentz force and Ohm’s law. Except that many physical situations may require a modification or a simplification of these equations to realistically capture way the physical phenomena of interest[459, 548].

Magnetohydrodynamic (MHD) (magnetofluid dynamics or hydromagnetics) covers dynamics of electrically conducting fluids like plasmas, liquid metals, and salt water or electrolytes. [298]. The principle of MD is demonstrated in Figure 5-12.

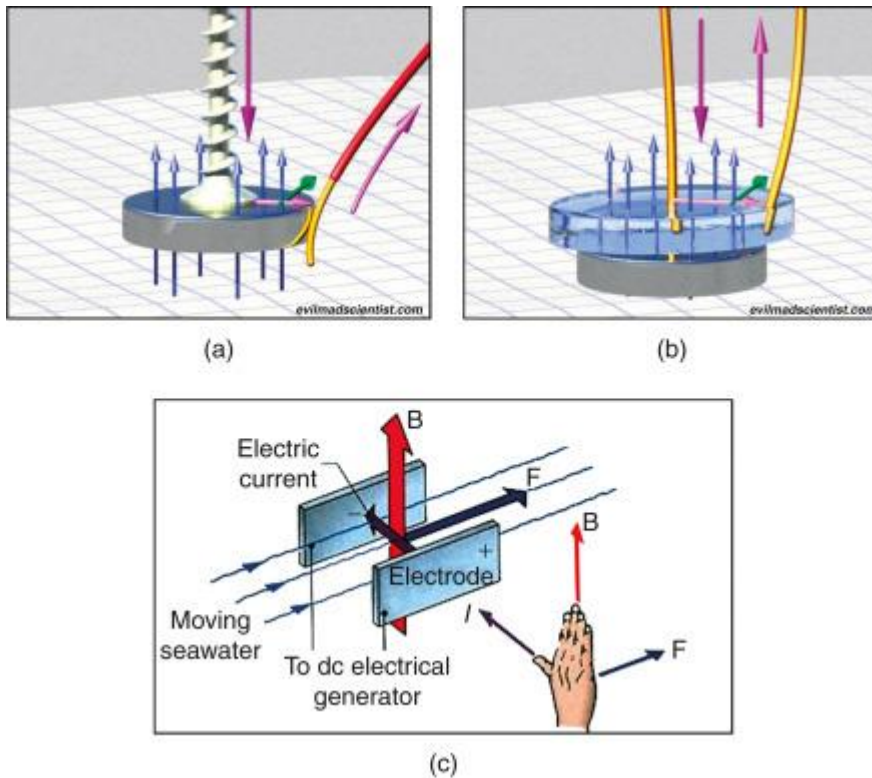


Figure 5-12: Induced Current in a Moving Conductive Fluid in the Presence of a Magnetic Field

Figure 5-12. demonstrates the how a magnetic field influences the conductive fluid flow. An orthogonal force is created by a current that runs down the screw and into the magnetic field, traveling at a 90° angle through the magnet and out the wire, causing the magnet to spin while it is magnetically attached to the screw. [298].

5.30.1.Principles of Operations

The basic design and construction of an MHD power system is illustrated in Figure 5-13.

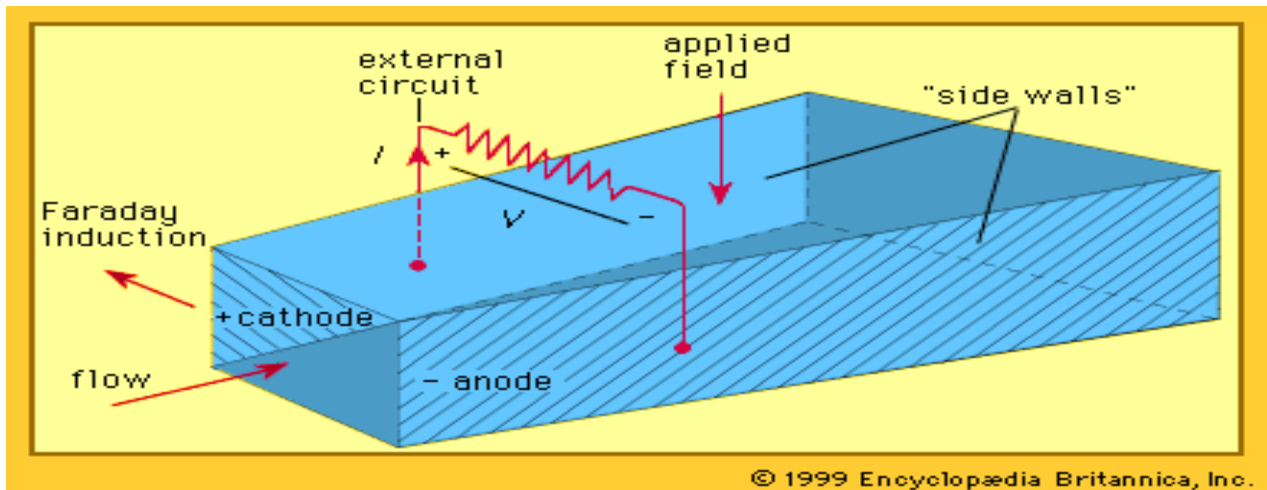


Figure 5-13: The basic structure of an MHD generator[306].

From Figure 5-13, the main elements of an MHD generator are the external circuit, side walls, applied magnetic field, the anode, and the cathode.

In an MHD generator the hot gas is accelerated by a nozzle before injection into a channel. Having a powerful magnetic field. An electric field developed that acts in a direction perpendicular to both the gas flow and the magnetic field in accordance with Faraday's law of induction, with the walls of the channel which are parallel to the magnetic field serving as electrodes and to enable the generator to supply electric current to an external circuit[306].

The power generation by the MHD generator per cubic meter of its channel volume is proportional to the product of the conductivity of the gas, the square of the gas velocity, and the square of the magnetic field strength. The generators in MHD systems operate competitively and with reasonable physical dimensions, if the electrical conductivity of the plasma is in a temperature range above about 1,800 K (about 1,500 °C, or 2,800 °F). The value of electrical conductivity be 10 to 50 siemens per meter can be obtained if an additive, generally about 1 percent by mass, is injected into the hot gas in form of readily ionizable alkali material, like cesium, potassium carbonate, or sodium, referred to as the "seed." Cesium has ionizing potential (3.894 electron volts), and potassium (4.341 electron volts) Economic operation requires that the seed material should be recovered as much as possible , [306].

The hot gas with its seed are pressurized to several million pascals and accelerated by a nozzle to a speed 1,000 to 2,000 meters (about 3,300 to 6,600 feet) per second then directed to the channel or duct, across which the magnetic field of high intensity is applied. For competitive power generation. A superconducting magnet is typically employed to supply a magnetic field in the range of three to five teslas across the channel. An electromotive force (emf) which acts in the direction perpendicular to both the flow and the field is produced with the walls parallel to the magnetic field serving as electrodes to provide current to an external electric circuit while the remaining two walls of the channel are electric insulators. An MHD system operating with a gas conductivity of 25 siemens per meter, an average magnetic field of three teslas, with average gas velocity of 1,000 meters per second can theoretically produce electric power with a density of about 250 million watts per cubic meter of channel volume[306].

The hall effect is the troublesome feature of a plasma MHD generator resulting from the behavior of electrons in the presence of both magnetic and electric fields. Electrons in plasma have higher mobility than ions. As the electric load current flows across the channel, the electrons in this flow experience a force directed along the channel which is referred to as the Hall effect named the discoverer, Edwin H. Hall. This forces the electric current to flow at an angle across the channel. Hall field, which is an additional electric field is established along the channel axis which in turn requires that electrode walls in a typical generator configuration be constructed to support this Hall field or that the Hall field is used as the output to drive current through the electric circuit external to the MHD system[306].

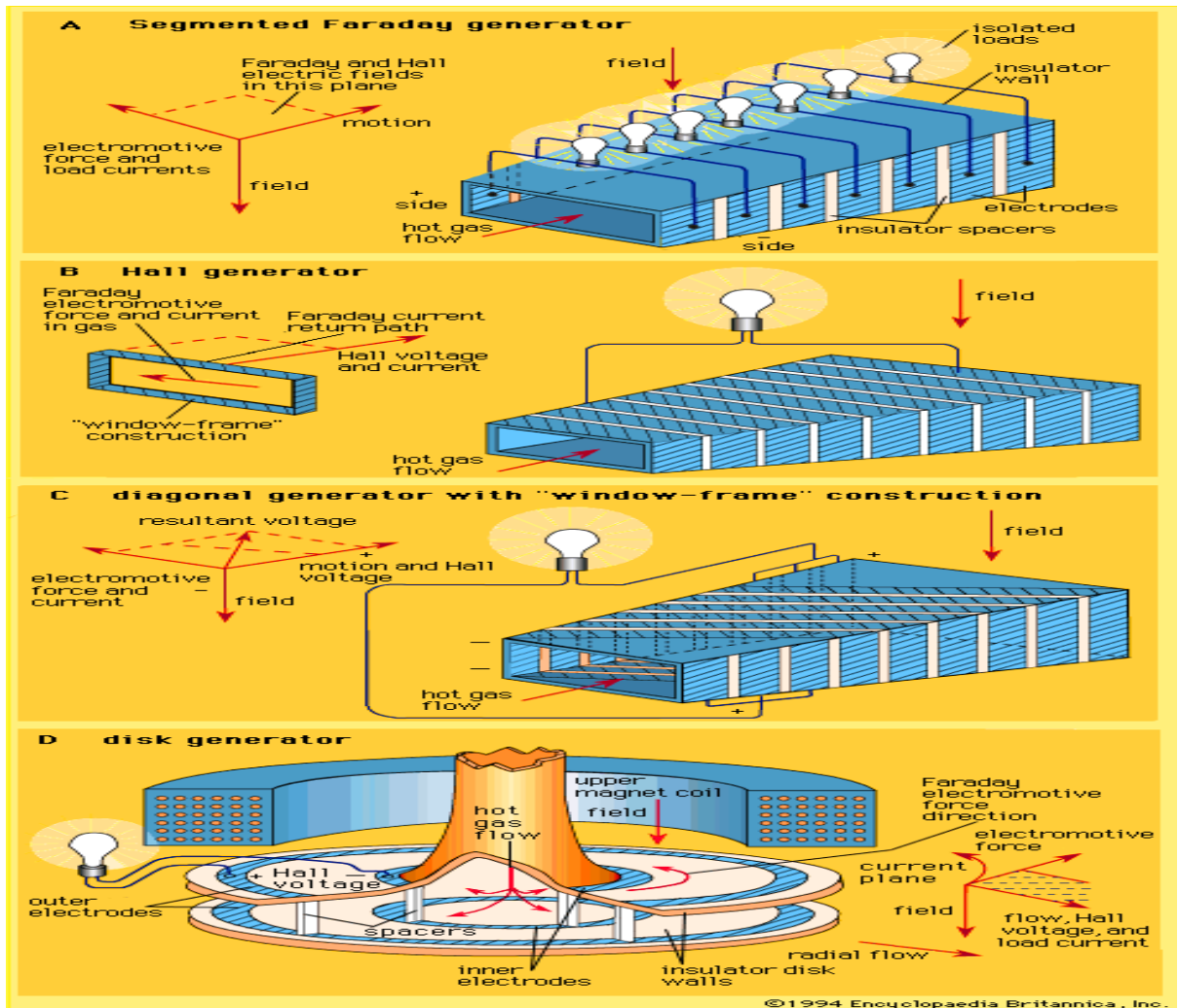


Figure 5-14: MHD generator configurations (A) Segmented Faraday generator. (B) Hall generator. (C) Diagonal generator. (D) Disk generator.

Figure 5-14 shows different generator configurations have been developed to accommodate the Hall effect. For a Faraday generator, the electrode walls are segmented and insulated from each other. This supports the axial electric field and electricity is taken out in a series of loads. The disk generator is an attractive alternative to the linear Hall generator when nonequilibrium ionization is used.

5.30.2. Major Types of MHD Systems

5.30.2.1. Coal-Fired MHD Systems

The choice of type of MHD generator is influenced by the type of fuel used and the application. In coal fired MHD systems for power generation, coal is burned at a temperature high enough to provide thermal ionization. As the coal gas expands along the duct or channel, its electrical conductivity drops with temperature. Power generation is essentially finished when the temperature drops to about 2,500 K (about 2,200 °C, or 4,000 °F). Coal fired MHD stations are more economically competitive if it is combined with a conventional steam plant to form a binary cycle. The hot gas is first passed through the MHD generator in a process referred to as topping) and then on to the turbogenerator in a conventional steam plant (the bottoming phase). Such a MHD power plant employing such an arrangement is known as an open-cycle, or once-through, system[306].

5.30.2.2. Other MHD Systems

Natural gas can be used as a fuel source in MHD while , conventional nuclear reactors can employ hydrogen, or a noble gas such as argon or helium, as the working fluid, but they operate at temperatures that are too low to produce the thermal ionization used in MHD generators. A form of nonequilibrium ionization using seeding material is important. Solar concentrators theoretically can provide thermal energy at a temperature high enough to provide thermal ionization, hence solar-based MHD systems have potential, subject to development of solar collectors that operate reliably for extended periods at high temperatures[306].

Pulsed MHD generators have found applications due to the need to supply provide large pulses of electricity in remote sites. The MHD system for this application basically consists of a duct, rocket motor, magnet, and connections to an electrical load. These generators are used as sources for pulse-power electromagnetic sounding apparatuses used in geophysical research and can achieve power levels up to 100 megawatts [306].

A variation of the usual MHD generator makes use of a liquid metal as its electrically conducting medium. This has a high electrical conductivity, although it cannot serve directly as a thermodynamic working fluid since it has to be combined with a driving gas or vapor to generate a two-phase flow in the generator duct, but can also be accelerated by a

thermodynamic pump also called an ejector and then separated from the driving gas or vapor before passing through the duct. The liquid metal MHD systems are limited in temperature by the properties of liquid metals to about 1,250 K (about 975 °C, or 1,800 °F). hence they compete with various existing energy-conversion systems that operate in the same temperature range[306].

5.30.3. Applications of MHD generator

Feasible applications of MHD generators include supply of power for spacecraft for both burst and continuous operations. Although both chemical and nuclear heat sources have been investigated, the nuclear sources are the preferred choice for applications such as supplying electric propulsion power for deep-space probes[306].

5.30.3.1. Vehicle to Grid (V2G)

Electric vehicles apply an electric drive traction system consisting of one or more devices for storage of electrical energy or electrical energy conditioning devices or one or more electrical machines meant to transform electrical energy often in stored form to mechanical energy which is transmitted to vehicle wheels to drive the vehicle. This is an all-electric vehicle, or a pure electric vehicle (BEV, for Battery Electric Vehicle). Storage often require regular recharging by connecting the vehicle to an electricity grid or by standard exchange of battery[549]. Electric vehicles are designed to limit the use of Internal Combustion Engine Vehicles (ICEV) and limit dependency to oil as energy source. Energy for electric cars is stored in fuel Cells (FCs), and or Ultra-Capacitors (UCs) as opposed to fossil fuel which is stored in a fuel tank. The main components of an electric vehicle system are the motor, controller, charger, power supply, and drive train. Electric vehicles available include the lower-end electric vehicles like Nissan Leaf and higher-end electric vehicles like the Tesla Model S. The EV are cleaner, can be used in peak load shaving, reduce grid infrastructure requirements, act as mobile distributed generation or electric power, etc. but their disadvantages include limited range, need new infrastructure for development, have long charging time; and are associated with adverse battery effects[549, 550].

There are several challenges associated with charging electric vehicles via the smart grid. These challenges include overloading, imbalance, under-voltage, etc. These issues with EV charging are managed via control called Vehicle-to-Grid (V2G) technology. The

technology enables electric vehicles to charge and supply electricity and services to the grid, via an aggregator, for compensation[549]. There are several V2G technology subsets like Vehicle-To-House (V2H) where the vehicle is in the owner's residence, Vehicle-To-Building (V2B) in which the vehicle is in a commercial building. In these arrangements, the battery power supplements the electrical charge of the local buildings without transferring power to the grid in the event of power failure in the grid[549]

The V2X technologies are associated with grid connected vehicles like the Vehicle to Grid (V2G), vehicle to house (V2H), and vehicle to vehicle (V2V), where V2G refers connecting of an electric vehicle to the electricity grid for battery charging and discharge. The vehicles are referred to as grid connected EVs (GEVs) [12, 56]. The EV represent a significant and radical change the transport sector engine driven vehicles and in the production of EV. The reason is that an electric vehicle is powered by electricity which can be generated from many sources like hydropower, wind, nuclear, wind, photovoltaic etc. An electric vehicle needs more energy compared the electrical needs of houses for heating and lighting. On the other hand, electric vehicles can be considered as electricity storage systems for the grid. Electric vehicles store electricity that can be used during peak periods to stabilize the grid. The main objective is to meet energy needs of customers under the constraint of not destabilizing the grid [549]

As the interest in alternative sources of energy and technologies increases, there is potential for massive penetration of electricity into the grid and widespread use of DER (distributed energy sources) is expected soon. For load management and resource scheduling, a collection unit, VPP (virtual power plant) may be applied. The vehicle-to-grid (V2G) technology enables fixed or parked voltage batteries to serve as distributed sources, for storage and release of energy at appropriate times, in as bidirectional power exchange between the AC mains and DC EV batteries. The bidirectional exchange of power is realized by use of bidirectional electronic power converters connecting the grid and electric vehicle (EV) batteries. Most bidirectional converters for V2G applications use of two dedicated power conversion phases – an AC–DC two-phase conversion step that assist in modifying the power factor, followed by a bidirectional DC–DC conversion phase, to provide voltage matching.[550]. The bidirectional electronic converters, used i.e. AC–DC (BADC) and DC–DC (BDC), facilitate G2V and V2G electricity transmission between electric vehicles and the grid. Bidirectional converters facilitate high efficiency energy conversion and in the e

transition from the conventional to electric vehicles, enable realization of a greener environment.

The V2G is a promising technology that enables idle or parked electric vehicles to act power plants for grid power supply, with ability to store electricity and release at appropriate times, to facilitate power exchange between grid and the electric car/vehicle. This approach increases generation capacity and improves power system stability, efficiency and reliability of the grid[550]. The development of smart grids and growth of electric vehicles has generated momentum for growth of vehicle-to-grid (V2G) technology. With V2G, one can use his vehicle to power his home, charge phones, power lights and even operate the fridge during time of high electricity price or during a grid outage and supply excess power to the grid when prices are favourable. The vehicle-to-grid technology (V2G) , which is also known as vehicle-grid integration (VGI), creates an extra power source when weather dependent renewable energy sources are not available. A home can use solar power to generate electricity during the day but use the electric vehicle to supply a secondary source of power if needed e.g. at night and sell excess to the grid[550].

Peak demand generally occurs between 5 p.m. and 11 p.m. for most grids globally. This is the time most private and public vehicles are parked at homes or parking stations. At this period, the vehicle to house (V2H) technology will enable the parked vehicles to supply electricity to home to meet demand peak demand while any excess can be exported to the grid. The electricity prices are generally lower during off-peak hours. This is therefore used to charge the vehicle can be for peak time use. The car can also be charged using solar energy like rooftop solar PV. The V2G technology can be applied by having electric vehicles clustered via an aggregator to offer grid power services like voltage regulation, load levelling, and peak shaving, at a lower cost and with less environmental impact which makes the smart grid technology ideal for deployment of V2G and hence play an important role in the energy transition[3, 56, 96].

The communication between the grid and electric vehicles facilitates sharing and exchange of information with respect to the state of charge of electric vehicles, availability of recharging stations and user data. Electric vehicles are in most of the time in a state of rest in the garages of the houses or in the parking lots, hence they can be easily charged by the G2V system and

be later used as a source of charge for the grid. The communication between electric vehicles and smart grid takes place in V2G discharge mode, from the vehicle to the grid, with the vehicle as source of distributed generation and G2V which is charging mode. Drivers benefit from the use of electric vehicles since electricity is cheaper than petroleum power. The electric vehicles also provide income to vehicle owners by selling power to the grid. [549].

5.31. Bagasse Cogeneration Power Plants

The content of this section on bagasse power generation is published in the authors publications [57, 390, 551]. Sugar industries have huge potential to contribute to the sustainable energy transition through electricity generation and production of biofuels. Sugar-producing countries generate huge volumes of sugarcane bagasse as a byproduct of sugarcane production. In this study, the performance of an operating traditional sugar factory is analysed for electricity generation and export potential. The challenges facing a traditional sugar mill are inefficient boilers, less efficient and back pressure steam turbines, and wasteful and inefficient use of steam turbine drives as prime movers instead of modern electric drives for the mills and cane knives. Others are the use of inefficient and energy intensive cane mill rollers instead of the diffusers which have low energy requirements. It was demonstrated that the cogeneration potential of sugar factory is quite significant but currently underutilized[296].

Sugar cane production leads to production of trash and bagasse as the main types of biomasses. Trash is the biomass residue left in the field after cane harvesting while bagasse is the fibrous lignocellulose remnant of cane milling process having moisture of 45 to 50% and 60 to 70% of its composition is carbohydrates. The main elements in bagasse are sugar, hemicellulose, pentosans, lignin, cellulose, and minerals, but the composition varies with variety, age of harvesting the harvesting method. Wet bagasse is about 25 to 30% the weight of sugar cane milled in the sugar factory, and it contains carbohydrates as predominant chemical constituent. Figure 5-15 below shows bagasse at the front section.



Figure 5-15: Bagasse fuel in a sugarcane bagasse cogeneration power plant

Bagasse cogeneration has proved to be a feasible successful means of grid electricity generation, additional revenue stream for sugar factories in Mauritius, India, Re Union Islands, and Brazil besides providing a cost-effective means of mitigating greenhouse gas emissions from power generation. Other competitive application of bagasse include use as a feedstock for bio processing industry like paper production, biogas generation, glucose derived chemicals, lignin derived chemical among others. In South Africa, the estimated 20 million tonnes of cane crushed per year can generate 960 MW of clean electricity while Kenya has a combined potential of 972 GWh annually with a combination of best practice in sugar production and bagasse cogeneration[59].

5.31.1.Sustainability

The challenges facing a traditional sugar mill are inefficient boilers, less efficient and back pressure steam turbines, and wasteful and inefficient use of steam turbine drives as prime movers instead of modern electric drives for the mills and cane knives. Others are the use of inefficient and energy intensive cane mill rollers instead of the diffusers which have low energy requirements. It was demonstrated that the cogeneration potential of sugar factory is quite significant but currently underutilized. Sugar factories can make significant contribution towards mitigation of greenhouse gas emission mitigation through supply of green electricity to the public grid. Modernization is required to increase the generation and electricity export

capacity through investment in new and modern high-pressure boilers, replacement of inefficient back pressure boilers (BPSB) with more efficient condensing extraction turbines (CEST), and reduction of factory steam consumption by electrification of mills and cane knife turbine drives among other measures [296].

5.32. Fuel Cells as Power Plants

The content of this section is published in authors publications [309, 491]. Fuel cells are electrochemical systems that convert chemical energy of a fuel like hydrogen and oxidizing agent often oxygen to electricity through a pair of redox reactions. Unlike batteries they continuously require supply of fuel and oxygen to sustain the process. In batteries the chemical energy comes from metals and their ions or oxides that are already in the battery except for flow batteries[552]. The fuel cell will produce power continuously on condition that there is a steady supply of the fuel and oxygen and are more efficient than combustion systems. The heat generated in the process of power generation can be put into thermal application thus further increasing efficiency through cogeneration. They are able to reduce building facility energy service cost by 20 to 40% [307]. The fuel cells are discussed in detail in chapter 15.

Stationary fuel cells are often used for commercial, industrial, and residential primary and backup electricity generation and can be very useful for power supply in remote locations, like spacecraft, isolated weather stations, large parks, telecommunication communication centers, off grid stations including research stations, remote military applications, and standby power supply sources for power stations[552]. The main advantage of fuel cell systems like hydrogen fuel cells is that they are compact, light and have limited moving parts to attend to hence low maintenance and can realize 99.9999% reliability [307].

Fuel cells are electrochemical devices used for the continuous conversion part of the free energy change in a chemical reaction to electrical energy. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2 , O_2), hydrazine (N_2H_4 , O_2), carbon/coal (C , O_2) methane (CH_4 , O_2). A fuel cell is a device akin a battery that continuously recharges as it generates electric power using low-temperature electrochemical

reaction oxygen and hydrogen. Unlike storage batteries whose main objective is to store energy, fuel cell fuel cells continuously generate if there is continuous supply of fuel and oxygen. Fuel cells employ an external or internal fuel-reforming process using any hydrogen-rich fuel can in different types of fuel cells. Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO₂ emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cells reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85% (Dutton, 2002) [308].

5.33. International Electricity Sources

Increased decentralization of generation which can further be enabled by the advances in smart grid technology and adoption leads to benefits like direct access to renewable energy, reduced emissions, energy security, and rural development. It is also important to note that countries are endowed differently with energy resources making sharing of resources an important sustainability strategy [388, 391]. As an example, France with its low carbon nuclear electricity dominated grid can share with neighbours heavily relying on fossil fuels, Ethiopia and Sweden have e huge hydro power potential which dominates their respective national grid power that can be shared regionally to de-carbonization of other countries grids. A sustainable energy strategy requires integration of the onsite power plants, regional grids, and diversified conventional grid components, and the operation of such diversified resources can be made efficiently feasible using interconnectors and smart grids to provide the necessary infrastructure and capability [80, 312].

5.34. Summary Of Power Plants and Energy Conversion Systems

The various power plants and energy conversion systems are summarised in Table 5-1.

Table 5-1: Summary of power plants and energy and energy

	Technology/powerplant	Energy Resources and prime mover	Characteristics Applications
1	Gas turbines -Open	Multiple combustion fuels e.g. natural gas, biogas, biomethane,	Power generation and aviation
2	Gas turbines-Open with CCS and CCU		
3	Gas turbine -Combines cycle	Combined cycle	Power generation
4	Geothermal wellhead	Wellhead power plants	Temporary and permanent power generation
5	Geothermal conventional	Dry steam technologies	Power generation
6	Hydro Run off river	Run-off River	Base load,
7	Hydro, storage	Storage	Base load and peak supply
8	Hydro pumped storage	Hydro, for Peak, dispatchable	Energy storage system, peak, dispatchable
9	Wind -offshore	Wind energy, wind turbine generator	Power generation and pumping
10	Wind -onshore	Wind energy,	Power generation and mechanical application
11	Solar photovoltaics		
12	Solar-thermal		

13	Bagasse power Plants	Bagasse, steam turbines	Cogeneration for heat and electricity
14	Coal power plants Coal without CCU/CCS	Coal, steam turbines	Power generation
15	Nuclear – Conventional	Radioactive fission	Base load power
16	Nuclear – Small Modular Reactors	Radioactive fission	Baseload and peak power, non-dispatchable
17	Wave power plants	Sea water and wind	Baseload, predictive
18	Tidal power plants	Sea water and gravitational forces	Predictive, non-dispatchable
19	Diesel power plants	They use diesel cycle engines and multiple fuels (HFO, IDO, natural gas, and biofuels)	Power generation, automotive and marine applications
20	Fuel cells	Hydrogen, biogas, biomethane,	Base load, peak, dispatchable
21	Grid Scale Battery Storage	Chemical energy, alternative power sources	Dispatchable, flexible applications
22	V2G	Storage batteries, alternative energy sources for power	Dispatchable, flexible applications

From Table 5-1, it is noted that various power plants, energy conversion systems and energy sources can be used to deliver grid power. They include power plants, energy storage, the vehicle to grid (V2G). Notable power plants, both conventional and non-conventional include diesel power plants, gas turbine power plants, hydropower plants, wind power plants, solar thermal and solar photovoltaic, tidal, wave and ocean thermal power plants, nuclear, coal, bagasse power, geothermal and fuel cells.

5.35. Chapter Conclusions

Power plants are units designed for generation of electricity from different energy sources. They systems include direct conversion systems like solar photovoltaics and fuel cells. Combustion based power plants like diesel power plants, coal, gas turbines, bagasse power plants and biomass. The fossil fuel-based power plants combustion types. V2G and grid scale storage perform energy storage or backup functions for intermittent sources for use when needed for balancing purpose. Power plants can be classified on basis of fuel; or energy source e.g., nuclear use nuclear energy, bagasse power plants use bagasse, coal power plants use coal, wind and solar power plants use wind power and solar respectively. Power plants like gas turbines and diesel can use different fuels but they are named based on the design of the prime mover.

CHAPTER 6:

TECHNOLOGIES AND CONCEPTS FOR THE ENERGY TRANSITION

6. Overview

This chapter various technologies, concepts, and energy management systems and infrastructure which act as enablers of the energy transition are identified for use in energy systems like greater integration of variable energy sources like wind and solar through enhanced energy system efficiency, intelligence and enhanced system capabilities like real time fault detection, prediction, outage management including self-healing and excess energy storage and power system optimisation. The enabling technologies include smart grids, energy storage, demand side management, behind the meter measures, modelling tools and generation approaches like decentralised generation and microgrids, cogeneration as well as technologies like carbon capture and sequestration and fuel switching which increase the sustainability of fossil fuel sources of energy and power. The enablers increase efficiency, reduce losses, increase power system resilience and uptake of variable and intermittent renewables which hold the key to the energy transition as abundant, green, and renewable sources of energy. The contents of this chapter are contained in publications listed as references [16, 61, 147, 283, 553-555].

6.18. Smart Energy Concept

Smart energy integrates and leverages renewable energy sources to establish environmentally friendly energy systems.

6.18.1.Importance of Smart Energy

The importance of smart energy is summarized in Figure 6-1.



Figure 6-1:Importance of smart energy systems.

From Figure 6-1 the benefits of smart energy systems include the creation of prosumers who are both consumers and producers of power, enhanced energy security, increased uptake of renewable sources and creation of intelligent energy systems capable of automatic ad remote control.

The emergence of technologies like edge computing, big data, and 5G, energy will increase energy usage across all sectors exponentially. Conventionally Power plants, telecom, and other major technology sectors conventionally use energy systems that do not provide insight into energy usage, waste, efficiency, and distribution which ensures a continuous lack of cost and energy efficiency and more negative environmental impact. Adoption of smart energy technologies by traditional energy systems reduces remote sites' energy waste by as high as 90%. The facing energy systems can be solved by, smart energy technologies to make industries function at optimal cost and energy use metrics with minimal impact on the environment and improving operator's visibility[556]..

Smart energy enables the achievement of their objectives through.

i.) Efficiency improvement

Efficiency improvement is one of the most significant incentives for businesses and organizations to shift towards smart energy. Smart energy enables stakeholders to monitor and actively and intelligently manage energy consumption. It also optimizes those energy sources,

to reduce energy costs by application of an IoT-oriented Remote Management and Monitoring (RMM) solution[556].

ii.) Instantaneous Optimization

With Industrial IoT (IIoT) or Industry 4.0, institutions can carry out their daily operations year-round. With equipment functioning optimally even at heavy operations load, idle times, varying weather conditions, and fluctuating power. The IoT optimized solutions can actively collect data on the energy needs throughout while noting idle times and overloads making distribution of energy and asset management become simpler and reduce energy wastage. Optimization leads to better demand management, minimize maintenance costs, increase asset longevity, and increase labor effectiveness by 20-40%.

iii.) Pre-emptive Outage Management

Data centers operate on 24/7 basis, making it easy for administrators to be notified of any risk of a power outage or equipment failure in advance. Visibility of these data centers is provided which alerts in real-time to continuity disruptions or malfunctions in the energy system which enable preemptive measures to be taken in the event of any disaster or downtime, and operators can potentially predict outages before they occur. This oversight capability can be applied to smart grid systems to deal with energy availability and stability issues. With RMM challenges. The embedded AI-enhanced analytics and insights enable data collection and analysis which helps identify errors and , send an alert, and easily switch to backup power before a power outage occurs[556]..

iv.) Integration of Renewable Energy Sources

Smart energy systems can help institutions to shift to renewable energy which is characterized by intermittent. This is achieved smart energy systems which have higher efficiency through use of artificial intelligence (AI) and machine learning technologies which when combined with energy storage solutions and intelligent infrastructures enable more flexibility in managing the supply and demand of energy and store excess energy [556].

v.) Reduced Carbon Footprint

The application of intelligent systems having storage solutions can reduce energy system carbon footprints by 90%. With smart energy systems companies track parameters such as carbon intensity, carbon saving, total emissions, and even how much they save from

renewable energy use on real-time basis. Which help to understand where the carbon emissions are high and hance take corrective actions [556].

6.18.2.Elements of Smart Energy Systems

To enable an extensive penetration of fluctuating sources into an electric grid, it is important to rethink the design of the energy system and switch to Smart Energy System approach. In the transition to 100% renewable energy system, the transport sector remains one of the most challenging and is unlikely that modal shift or electrification will completely remove the dependence on liquid or gaseous fuels in some modes of transport, like heavy-duty trucks, shipping, and air travel. It is therefore important to model production cycle of needed hydrocarbons and, create flexibility that will enable an extensive penetration of fluctuating sources into the electric grid[557] The main elements of a smart energy systems are illustrated in Figure 6-2.

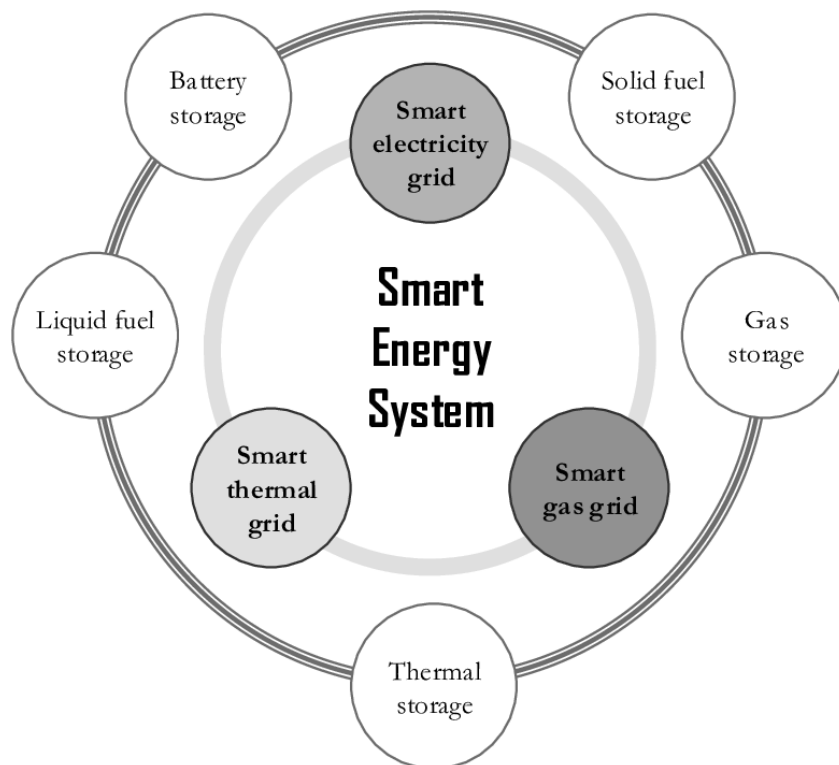


Figure 6-2: Elements of smart energy systems

From Figure 6-2 It is noted that the main elements of a smart energy system are the energy storage of different types i.e., liquid fuel storage, thermal storage, gas storage, solid fuel storage and battery storage. Other elements are smart grids i.e., smart electricity grids, smart gas grids and smart thermal grids.

6.18.3.Applications of Smart Energy

Smart energy implementation is currently widespread and is useful across almost any industry. The major sectors that leverage this concept and system are as follows:

- i. Industrial facilities which require optimization of operations by applying IIoT sensors to minimize costs and ensure that the assets last longer.
- ii. Data centers which need continuous monitoring, and hence smart energy solutions help them execute contingency plans if there's energy fluctuation or a power outage.
- iii. Power plants can use the IoT-integrated systems for optimization of energy production and maximize the uptake renewables use while integrating energy storage.
- iv. The transport sector particularly the Electric vehicles need smart energy solutions for their charging stations to reduce their cost, maintain power system stability, system maintenance, and carbon footprint on the planet.
- v. The telecommunications sector needs requires smart energy solutions to operate efficiently especially with the emergence of 5G, the rate of data usage and number of phone contuse with expected than 3.6 billion 5G connections worldwide by 2025. High financial and operational costs necessitate monitoring and efficient usage [556].

6.18.4.Smart Energy Systems Benefits, Challenges, and Opportunities

Advances in in artificial intelligence (AI) technology, the control and management of MESs is rapidly adopting of intelligence which use a variety of smart calculation and measurement methods, like smart monitoring of energy information, smart collection, analysis, and processing of data, etc., for effective processing of information transmission, flexible application of energy resource, and real-time coordination of system operations. Intelligent

control continues to integrate technologies such as fuzzy logic, big data, and deep learning to perform various forms of power generation prediction, load prediction, and uncertainty prediction for various distributed energy sources. All these capabilities support distributed decision-making, collaborative autonomy, security protection, transaction supervision and integrated services of the MES[313]. Figure 6-3 demonstrates a smart energy environment.

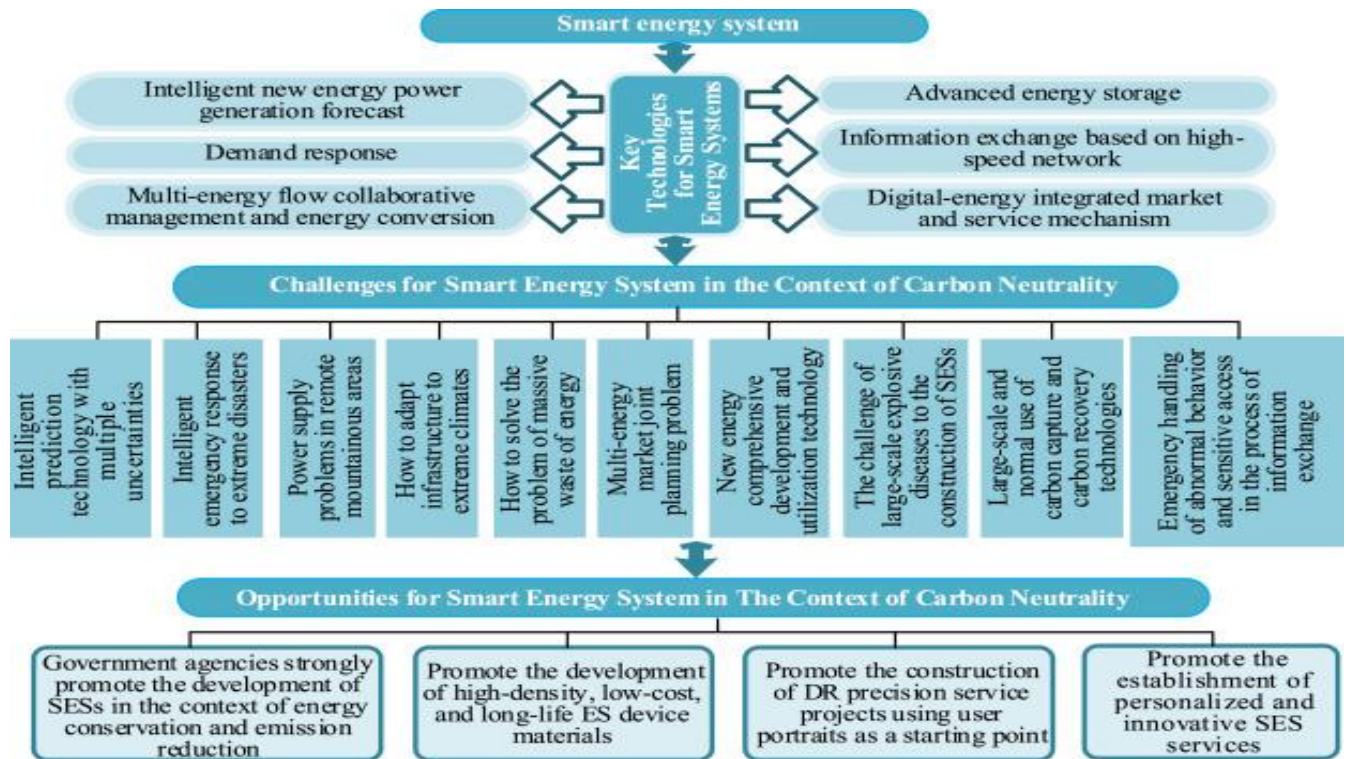


Figure 6-3: Summary of smart energy concept [313]

From Figure 6-3, it is noted that various opportunities exist for application of smart energy systems including government agencies, development of low cost and long-life energy devices, distributed resources exploitation and development. The challenges facing development of smart energy systems are also many and include risk of access to critical information, cyber security issues, operation in areas with extreme climate and environmental conditions and operation in remote areas with power supply issues.

Smart energy systems incorporate key technologies and energy sectors like electricity, heat, cooling, and information technology and some level of intelligence as shown in Figure 6-4.

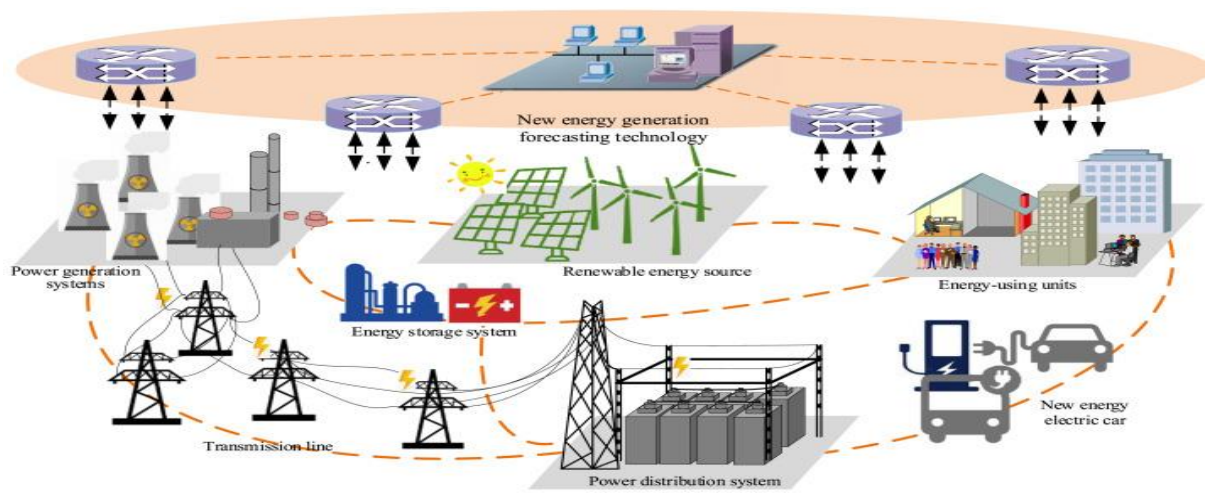


Figure 6-4: Smart energy system incorporating a variety of key technologies.

From Figure 6-4, it is noted that smart energy systems incorporate electricity, heat and cooling infrastructure and resources with information technology playing an integrating role. System intelligence is a key characteristic of smart energy systems in the integrations of various functions and energy systems and resources.

New energy power generation prediction technology has been widely used in photovoltaics, wind energy and other variable and intermittent fields. It is possible achieve hourly, minute, and second-level prediction performance with this technology and thus it supports new energy generation's safe and stable operation[61, 313, 558].

6.1.5. The traditional Grid

The content of this section is published in conference paper[61] co-authored by Prof. Oludolapo. The power grid consists of transmission lines, substations, transformers and other meant to deliver electricity from power plants to end users [61, 73]. The grid usually consists of many power plants of different technologies and characteristics, networks, generators, grid operators and different stakeholders applying different communication levels. The coordination in traditional grids, is usually manually controlled[2, 326]. The traditional electric power grid technology is over 100 years old, and its design is meant to feed electricity from large central power plants using high voltage network, covering considerable distances

to deliver power to end users via lower voltage distribution network with little flexibility[12, 61]. Over years now, electricity demand has grown rapidly mainly due to social-economic development and industrial growth but the supply mainly comes from cheap traditional sources of energy like coal, gas and petrol that are associated with release of greenhouse gas emissions (GHG) to the atmosphere that are responsible for climate change[62, 112]. The electricity grid is being modernized towards advanced consistency, less costs, and greater efficiency through more uptake of renewable energy, advanced control technology and two-way communication. There has been a growing need for substation modernization to cope with fast growth of the grid, growing consumer needs, and technological innovations leading to grid transformation. The Smart grid can help accomplish these technological reformations across the grid in power n generation, transmission and distribution, through more use of sensors, communication and computers[65].

There is a global transformation of the traditional power system that is unidirectional in structure and operation to a configurable and participatory two-way structure where actors or participants can interact with one another [3, 61, 74]. The main motivation for this transformation is advances in communication, power electronics, and computer technology and increasing need to accommodate the variable renewables and electric cars on the power grid while maintaining. maximum reliability, quality of service, with minimum economic and ecological costs, while maintaining maximum safety for equipment and users and always keeping the voltage and frequency values within the permitted range [12, 96, 559].

6.19. Smart Grids

The content of this section is published in the journal paper[16] and conference papers[61, 147], co-authored by Prof. Oludolapo. The energy transition towards sustainable energy systems requires advanced technologies like management systems and renewable energy generation and storage which can be enhanced by adoption of smart grids. To manage operation of such complex systems requires the integration and coordinating several power system components like advanced sensors and smart meters as main data sources in the era of big data, wireless communication, and application of the internet of Things (IoT) [314, 315]. Such data acquired should be stored, processed, and analyzed to generate the necessary output for efficient deployment of smart grids and operation of power stations demand and supply

while integrating renewable energy and clean sources of energy and demand side management options. Very important in a modern power system is energy fuel efficiency, reduction of emissions and waste minimization[2, 3]. The benefits from such a modern grid include better asset management, enhanced operations planning, better monitoring and control, reduced cases of voltage instability, accurate prediction, and fault detection in a power system. Such advanced system also faces several challenges in implementation related to aspects like data uncertainty, data security, data quality, and data complexity[314, 315].

Smart grids have been identified as key building blocks for transition to future sustainable energy with less greenhouse gas emissions and better quality of energy services. It has been established that smart energy systems are not just an issue of technological development but should also consider the operation and impact of grids in which the energy technologies are applied or used. The underlying physical energy network is a network of stakeholders, who include various consumers, electricity producers, and power grid operators, with vested and often competing or conflicting interests[560]. This requires regulation to define or guide the relationship between these competing stakeholders. Smart grid applications should adapt to the local grid characteristics like., population density, diversity, and consumption patterns. Smart grids are quick to adapt and influence the operation, policy direction, and regulatory mechanisms. Global warming concerns, serious energy shortage and sustainable development targets are today urgent requirements globally. Integrating smart grid technologies, increasing the use of sustainable energy resources and low-carbon emissions from the power sector, is important route to sustainable global development[560, 561].

The Smart grid is the direction and trend of power industry development based on the physical grid that combines advanced information & communication technology with operation technology to the traditional grid. Smart grids link power generation, transmission, system transformation, power distribution, electricity consumption and dispatch in two-way participatory manner by coordinating the needs and functions of different participants in the grid environment enabling the system to operate with higher reliability and system stability. Smart grids facilitate the optimization of the electricity mix consisting of both renewable and nonrenewable sources by application of computer programs and hardware to manage power generation, transmission, and distribution resources. The smart grid technology is a product of the fourth industrial revolution (4IR) which is important to achieve fastest technological

reforms in electricity generation, transmission, and distribution (T&D) because of growing application of computers, sensors, sensors, and communications. By plugging abilities and Thing (IoT) in the traditional electricity grid, the resulting smart grids can optimize energy solutions through flexibility in the management of the diverse energy systems, enhance operational insights, improve maintenance forecasting and self-healing abilities, and create more a more secure and safe power system. The study recommends conversion of the traditional grid to smart grids as a technical solution with significant financial/economic, social, and environmental benefits in the sustainable energy transition. To realize this, it is necessary to build the institutional capacity and put in place policy measures that promote the development of smart grids this like micro grids, modern energy storage, decentralized generation and development of renewable energy resources and technologies.[16, 61]

The electricity grid is undergoing significant changes because of the proliferation of variable renewable energy resources, intelligent sensors, high-speed signal processors, among other developments. Smart grids (SG) can be said to be modern electric power grid architecture having higher efficiency and dependability. Smart grids present the greatest potential advances in the global sustainable energy transition[21, 562]. Smart grids were proposed as a result of rapid growth in demand and users thus the need for efficient distribution of the electricity, reduced losses, high quality and reliability, and high security of electricity supply[12, 563] Energy transformation and sustainability is a global challenge, for many developing countries, facing energy-related issues like wide demand–supply deficiency, over dependency on fossil energy sources, and low access to clean energy. The smart grid technology has ability to address these challenges and support a smooth transition from traditional to smart energy systems [3, 56, 62]. The smart grid uses intelligence for integration of user actions connected to the system like consumers, generators, and other stakeholders for delivery of sustainable, economic, and electric power [3, 61, 564]. A smart grid makes use modern communication and computer technology to operate and control the electricity network to better handle potential power system failures[12, 61, 565]. Therefore, a smart grid is equipped with advanced communication, automation, and information technology systems (IT) that enable real-time bidirectional monitoring and control of electricity and information between sources of power and consumer appliances.

A smart grid marks a shift from centralized power generation to decentralized power generation. Smart grids seamlessly integrate the three power system functions of generation, transmission, and distribution are integrated evolving the grid into integrated smarter system. The smart grids facilitate the integration of all forms of power generation and converts a consumer into a producer and consumer (prosumer) enabling households to generate and store electricity both for sell and own use courtesy of the two way power flow and communication facilities[566].

The smart grid can empower customers with real-time control and the choice between storing, generating and consuming electricity based on prevailing cost, availability of energy and demand for electricity. Through demand response (DR), smart grids enable customers to change their electricity consumption pattern by shifting or reducing their consumption from peak to off-peak hours thus making power flow more interactive, efficient, customer friendly and more environment friendly[566]. The concept of smart grid is an addition to existing or prospective smart meters which allow accurate energy flow analysis for power utilities, increase uptake of renewable energy sources and facilitate sharing of energy with increased system throughput[567]. The modern should simultaneously address the challenges of increasing environmental pollution, greenhouse gas emissions, and diminishing of fossil fuel reserves and climate change[68]. Smart grids facilitate decentralized decision making and enable active participation of prosumers and other assets not owned by the grid. They additionally facilitate monitoring of energy flows, manage prosumers' energy supply and demand changes which may be rapid to attain local energy balance, and optimize the electricity flows in the power systems[568].

The traditional grid was designed to connect far away consumers of electricity from central power plants using a rigid one-way power flow arrangement. On the other hand, smart grids are designed to provide a two-way flow of power and information. This has been made possible by developments and advances in information technology, communication and power electronics technology making it possible to accommodate new energy carriers, as well as decentralization of power generation, and higher uptake of variable energy sources like wind and solar and variable loads like electric vehicles. This will enable higher access to electricity over and beyond the capability of the traditional grid [3, 21, 62]. Today, an ideal electricity grid ought to be a two-way system with power generation from a mixed multitude of big, medium and

small, distributed plants supplying grid power in an optimized mix mode [106, 569]. This will facilitate maximum and optimum absorption of variable and intermittent renewable sources of energy like wind and solar have huge potential to contribute to the grid as sustainable and renewable energy sources needed for the global energy transition[3, 21, 58, 110].

6.19.1. Smart Gas Systems

Smart gas grids are designed to link electricity, heating, and transport sectors and facilitate enables use of gas storage infrastructure to create additional flexibility in the three sectors. The gas may be refined to a liquid fuel which need then liquid fuel storages. The gas grids can also be connected to biogas/biomethane systems for supply of biomethane which addresses sustainability challenges [570-572].

The basic requirements for Smart Energy Systems is that individual energy grids should be smart, as well as all other energy grids like electricity, thermal and gas and these smart grids from all sectors should be connected for better exploitation and synergies across the different energy grids. With smart energy systems, one can use electricity from all sources like wind and solar and other sources of energy from sectors like heating and transport. This creates a flexible use of different energy sources and infrastructures e.g. energy storage, from thermal and electric storages.

6.19.2.Electro Fuels

The transport smart energy concept emphasizes the use of electric vehicles and direct electrification of the entire sector since direct use of electricity is more efficient compared to stored energy in fuels. The smart energy system approach emphasizes production and use of renewable fuels like biomethane and bio-hydrogen. Where direct electrification may not be efficient and reliable.

The use of electro fuels is another important aspect of the smart energy concept. Electro fuels are made by merging a carbon source with electrolytic hydrogen to make hydrocarbons or are made by the merging of a nitrogen source to produce ammonia. The source of carbon for electro fuels can be obtained by carbon capture and or direct air carbon capture, biomass gasification, or biogas [573]. Electro fuels system is created by integration of transport, electricity, and gas sectors via the Power-to-liquid and Power-to-gas concepts. The process involves conversion of electricity by means of electrolysis to produce hydrogen which is

used as a booster for gasified or fermented biomass in a hydrogenation process or it can be merged with carbon dioxide emissions from energy or industrial plants and converted to fuels. These fuels produced these way are called electro fuels or bio-electro fuels and CO₂-electrofuels [565].

The technology involves the following process.

- i. Conversion by electrolysis in electrolyzers to produce hydrogen gas
- ii. Application of gasification and fermentation to biogas and producer gas for use in carbon production.
- iii. Application of chemical synthesis to synthesize the electro fuels from the hydrogen and carbon.

6.19.3.Smart Thermal Systems

These grids incorporate district Heating and Cooling connected to electricity and heating sectors. They facilitate use of thermal storage which create additional flexibility and the recycling of heat losses in thermal energy systems [574, 575].

Technologies in thermal or heating applications can be classified into district heat or utility-scale heating technologies like fossil fuel boilers that use coal, gas and oil fueled), direct electric heating and utility-scale heat pumps, concentrating solar thermal power (CSP) parabolic fields, geothermal and solid biomass district heat plants. Heating maybe done using small scale fossil fuel boilers using gas or oil, use electric heaters for direct heating and heat pumps that use solid biomass and biogas [576].

6.19.4.Power to Gas

Power-to-Gas (P2G) is a technology used to convert electrical energy to gas and is referred to as gaseous fuel from non-biological origin. This technology is mooted as a means of utilizing cheap or otherwise curtailed electricity to make advanced transport fuel, while at the same time enabling intermittent renewable electricity application through grid balancing measures and decentralized storage of electricity [577].

Alongside the integration of power-to-transport technologies with other systems aspects of power-to-gas technologies are developed. The state-of the-art of power-to-gas concept aims at

boosting hydrogen, green gas and green liquid fuel production within the gas, transport, and electricity sectors which offers a solution to challenges of fluctuating renewable energy[565]. The aim of Smart Energy Systems is to achieve better energy solutions for the energy thermal sectors. A coherent approach to a total smart energy system creates several synergies. Which develops the best solution for the entire system as well as best solutions for individual sub-sectors.

- i. Electric power for heating facilitates the use of heat storage instead of electricity storage which is more efficient and cheaper and offers combined heat and power which is more flexible.
- ii. Electricity can be used for thermal application for balancing in energy markets, etc.
- iii. Biomass can be converted to gas and liquid fuel using steam produced by cogeneration plants which also produce low temperature heat for district heating and cooling grids.
- iv. District heating can supply process heat instead of generating own heat for the plant.
- v. Power from hydrogen produced in hydrogenation facilitates the use of cheaper and more efficient gas storage.
- vi. Use of combined heat and power plants (CHP) for space heating facilitates the use of low-temperature district heating from the same energy source used for power generation, which is efficient, and cleaner based on fuel used.
- vii. Grid power can replace fuel while at the same time provide for electricity balancing during peak ours
- viii. Excess heat from industry and power plants can be applied in district heating for buildings.
- ix. The hypothesis in Smart Energy Systems concept is founded on the understanding that a feasible least-cost strategy may not be found within existing limits of the individual systems. and therefore planners should put each of the sub-sectors into coherency of the entire energy system in search of synergies existing dynamically and statically between individual sub-systems to identify the best t options [565].

6.19.5.Smart Energy Modelling

Smart energy systems models should provide similar and parallel analyses of gas grids, thermal and electricity systems. Examples of such models are EnergyPLAN, developed to

enable an hourly basis analysis. The main role of the smart energy models is to design national energy planning strategies based on technical and economic analyses of energy and investment options. EnergyPLAN emphasises complete energy system as a whole in which electricity smart grids can be coordinated with use of renewable energy for other applications in addition to electricity production[565].

In EnergyPLAN the renewable energy is converted to other carriers like heat, synthetic gas, hydrogen, and biofuels as well as application of energy conservation and efficiency enhancements through strategies and combined heat and power which have potential to replace and reduce consumption of fossil fuels. As an effective modelling tool for smart energy systems, EnergyPLAN can compute hourly electricity balance, hourly district heating and cooling balancing and hourly hydrogen and natural gas with contributions from biogas, gasification, electrolysis and hydrogenation.[575]

6.20. Decentralised Generation

The content of this section on decentralized generation is published in the conference paper[558] co-authored by Prof. Oludolapo. Distributed energy systems (DES) have significant potential to enhance sustainability of electricity systems. Decentralized generation systems are small-scale power technologies generally ranging between 3 kW– 10 MW located very close to consumers to provide an alternative or enhancement to the centralized or conventional power system. The DGs are connected directly to the distribution system or on the customer side of the meter, which significantly reduces the transmission and distribution losses of the power system. The high consumption of fossil fuels and global commitments to reduction in energy related emissions has generated huge interest in renewable energy resources for use in power generation. This has increased the opportunities of utilizing decentralist generation systems in power generation.

6.3.1. Introduction

There is an evolving paradigm shift in the way electricity is produced from large, centralized generators to small generators using non-conventional and renewable energy sources which are connected to distribution network. The small generators originally used for back up and not synchronized to the grid are now used as primary source of electricity in the form of Microgrid[578]. Effectively, the small power generators which are based distributed energy

resources (DER) are now a promising option to satisfy the ever growing power and thermal energy demand with an emphasis on reliability and power quality[578].

The renewable DG systems may be connected to the grid for peak shaving or as a stand-alone system to serve a particular load or an area. Integrating renewable DGs to the power system has many benefits as well as threats if not well coordinated and integrated into the power system. High penetration of renewables can cause several adverse effects on the distribution systems. like voltage rise, reverse power flow, high line losses, creation of harmonics and reduction in voltage quality. Decentralized power systems units should be designed and operated within limits to maintain optimal quality of the power system There is therefore need for optimal sizing and location of renewable decentralized generation (DG) units in the distribution power system for technical and economic benefits. The penetration of renewable decentralized generation systems is considered as a significant contribution to the world energy and environmental crisis.

There is a need to develop more flexible electricity networks for the purpose of power distribution as opposed to the current practice in centralized power systems where the operators just transmit power and keep the grid stable. A desirable future power grid should have inbuilt flexibility approaches and methods like demand-side response, intelligence, and energy storage. This marks the transformation to distributed generation is which is a new approach in the in the power sector[565]. There are many definitions for decentralized generation e.g., the Anglo-American often use ‘embedded generation’, while in North America, it is often referred to as ‘dispersed generation’. In Europe and parts of Asia, it is often referred to as ‘decentralized generation’.[12, 21]. Distributed generation (DG) is proving to be a very important more important future generation system that is rapidly evolving in competitive electricity markets. Distributed generation is generally defined as an electric power generation system within distribution networks or on the customer side of the network [61, 579].

Therefore distributed generation does not have to supply reactive power to the power system[579]. The distributed generation units are installed and connected directly to the distribution network or they can be connected to the network on the customer site of the meter[579]. A transmission system is usually operated by an independent institution that is not involved in power distribution and retailing or sale of power to consumers. The

distribution network is a low voltage network operated or owned by power retailing or selling companies who deliver power to the consumer meters[579]. Distributed generation units can be owned by independent power producers or by the customers. Distribution companies can only install their own distributed sets for different applications. The number of units needed may be determined by whether decentralization is partial or fully implemented. Completely decentralized generation does not need any transmission lines and large-scale centralized power plants but in partial decentralization, distributed generation accounts for a fraction of the local energy demand[29, 579].

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6.3.2. Design, Construction and Operation of Decentralized Energy Systems

A decentralized power system is based on distributed generation, demand response and energy storage in its design and operation[581, 582]. Several recent advances in energy technologies

and grid infrastructures have increased the interest in the use of distributed generation (DG) resources for grid electricity generation. The exploitation of distributed generation (DG) for grid electricity is subject to technical constraints to extend distribution and transmission networks to some areas as well as the deregulation of the electric power sector. There are many benefits of distributed generation depending on the characteristics of the sources like photovoltaic (PV), diesel engines, wind power systems, type, and characteristics of the loads, availability and access of local renewable resources and power grid network configuration. The benefits can be technical, environmental, social, political, and economic benefits like line-loss reduction, system reliability improvement, local revenue, employment and economic benefits and reduction in environmental pollution. The various benefits can be optimized by optimal sizing, optimal location, as well as optimal configurations [580]

The increasing presence of distributed generation systems based mainly on variable renewable energy sources as well as growing variable load users like, plug-in electric cars connected to the grid and lower voltage points have rendered central power transmission and distribution networks invalid [583]. There is a general shift to small and distributed power plants that use predominantly renewable sources of energy for grid electricity generation in a system that supports a bi-directional flow through transformers[584]. The distributed energy resources (DER) are slowly playing a dominant role in remote and isolated areas. Decentralization. The decentralization of power generation gathered momentum when economies of scale ceased to be a significant factor because of innovation and adoption of smart grids. The global annual increase in distributed generation capacity has surpassed the centralized electricity systems which is an indicator of growing demand and use of decentralized generation[585].

To maximize the use of DER technologies needs the development in a systemic architecture and policy measures that can balance the interests of new players with the existing centralized model players. An optimal combination of DER and centralized generation is one of the most effective and efficient approaches in the energy transition. These requires principles and mechanisms to enable seamless integration of the centralized and decentralized power systems[585]. The main beneficial effect of distributed generation is it leads to increase in nodal voltages. The use of variable loads like electric cars on distribution networks puts significant pressure on need for nodal voltage control using a flexible and resilient grid with

abilities beyond mere decentralization of grid power generation [583]. Decentralized generation technologies have resulted in increased viability of small energy systems while more use of information technologies has created to new opportunities in the management of energy infrastructure in a less hierarchical and flexible manner. Decentralization has therefore created higher opportunities in the transition to a more sustainable energy future through application of efficiency measures, reduced emissions, and lower costs.

6.3.3. Sizes of Distributed Generation Units

In terms of size, The Electric Power Research Institute defines distributed generation as one that ranges from ‘a few kilowatts up to 50 MW’, while the Gas Research Institute, defines distributed generation as ‘typically ranging between 25 and 25 MW while Preston and Rastler suggest size ‘ranging from a few kilowatts to over 100 MW’. On his part Cardell defines distributed generation as generation ‘between 500 kW and 1 MW’. Since renewable energy is generally produced within decentralized networks, the progress and advances in distribution grid is strongly influenced by progress in smart grid technology [579]

Based on their size, or capacity, distributed generators can be classified as micro, small, medium, and large as summarized in Table 6-1.

Table 6-1: Categories of distributed systems based on capacity[579].

Category		Capacity
1	Micro	1 watt - <5 kW
2	Small	5kW – <5 MW
3	Medium	5 MW -< 50 MW
4	Large	50 MW- <300 MW

From Table 6-1, it is noted that distributed generators vary in size from as low as 1 watt to 300 MW. Microsystems vary between 1 watt and 5 kW, small size generators between 5 kW and 5 MW, medium between 5 MW and 50 MW and large between 50 MW and 300 MW.

6.3.4. Technologies and Energy Sources for Distributed Generation

Decentralized generation system (DG) technologies are modular generators used to supply alternative and conventional power as a means of reducing power interruption. These systems have wide ranging limitations, characteristics, and strengths. Decentralized technologies can broadly be classified into renewable and non-renewable based on the source of energy and operations. Various technologies used are summarized in Table 6-2.

Table 6-2: Technologies and power plants for distributed generation[579]

	Technology	Typical Capacity Per Module
1	Combined cycle gas turbines	35 MW -400 MW
2	Internal combustion engines	5 kW -17 MW
3	Combustion turbine	1 MW -250 MW
4	Micro gas turbine	35 kW - 1 MW
5	Stirling engines	2 kW – 10 kW
6	Small hydro	1 MW -100 MW
7	Micro-hydro	25 kW- 1 MW
8	Wind turbines	200 watts -5 MW
9	Photovoltaics arrays	20 watts -100 kW
10	Solar thermal -Central receiver	1 MW -10 MW
11	Solar thermal -Lutz system	10 -80 MW

12	Biomass gasification	100 kW -20 MW
13	Fuel cells- phosphoric acid	200 kW- 2 MW
14	Fuel cells- molten carbonate	250 kW- 2 MW
15	Fuel cells-Proton exchange	1 kW -250 kW
16	Fuel cells-Solid oxide	250 kW- 5 MW
17	Geothermal	5 MW -100 MW
18	Ocean thermal	100 kW- 1 MW
19	Battery storage	500 kW -5 MW

From Table 6-2, it is noted that different technologies and energy sources with different capacity ranges can be selected for use in decentralized generation. The largest units in decentralized generation are combustion engines and gas turbines.

6.4. Micro Grids

The content of this section on microgrids is published in paper [147] co-authored by Prof. Oludolapo. Micro grids constitute the ultimate form of decentralized electricity, heat, and cold supply whose operations separated from the main distribution system i.e., autonomous or connected to the distribution system i.e., grid connected. Grid-connected micro grid can be of help during a system fault, by supplying power to the main distribution system, feeding part of its loads for fault detection and service restoration. Micro grids have emerged as a competitive alternative to the final delivery of energy to consumers in combination with on-site production of heat. Distributed generation grouped in micro grids can introduce a richer set of tools for supply of o heat and power, at higher reliability, security, flexibility, and power quality in the conventional grid. A micro grid is typically managed through a central controller that monitors the system parameters, coordinates energy resources, balances load and controls electrical loads, and disconnects and reconnects of the micro grid to the primary grid.

Micro grids with no central controller are not common but are technically feasible, with distributed energy resource having an individual controller and the individual controllers

operate in a coordinated manner. Micro grids can be an effective option to increase the energy resilience, by providing a functional electric power system capable of operating independently of the main grid. The main grid usually supplies primary power, while the micro grid provides secondary dispatchable power in the event of a grid failure. Emergency diesel generators can provide power directly to loads in the event failure of the primary grid and the micro grid. Proper design and planning of microgrids is important for them to yield all the advantages of the distributed energy concept for the power systems, both local and the clinked central power system. This calls for a reliability -oriented design for microgrids that utilise a large share of the variable and intermittent renewable energy-based, and power electronics-interfaced distributed energy resources. Experience has shown that the power electronics used are prone to wear-out failure and can potentially have adverse effects on the on the performance of the entire power electrics dominated power system. The many benefits associated with application of microgrids have contributed to their significant growth and penetration in decentralized power generation globally. However, challenges are still encountered with respect to design [586].

Microgrids constitute a technology option that can help deliver a sustainable and efficient power system by employing distributed or decentralised energy resources for efficient generation and supply local electricity load and increase the reliability of a local distribution network[587]. A microgrid is defined as a community of power sources which work together create a network of energy supplies and having a singular point of autonomous control, with ability to offer non-stop power generation to end users through automatically switching between the connected sources of energy. The microgrid concept has gained popularity recently because of the need for modernization of the grid modernization, reduction in the use of fossil fuel-based power generation, and maximum integration of new technologies and variable renewables. Physically, microgrids are electrical structures interconnecting small, decentralized generation sources located close to the load centers or point of electricity consumption. Microgrids are often connected to larger distribution power systems but have ability to operate independently [61, 322, 587]. With the ever-changing energy landscape, microgrids offer a sustainable energy solution. Figure 6-5 shows the general arrangement of components or elements of a microgrid.

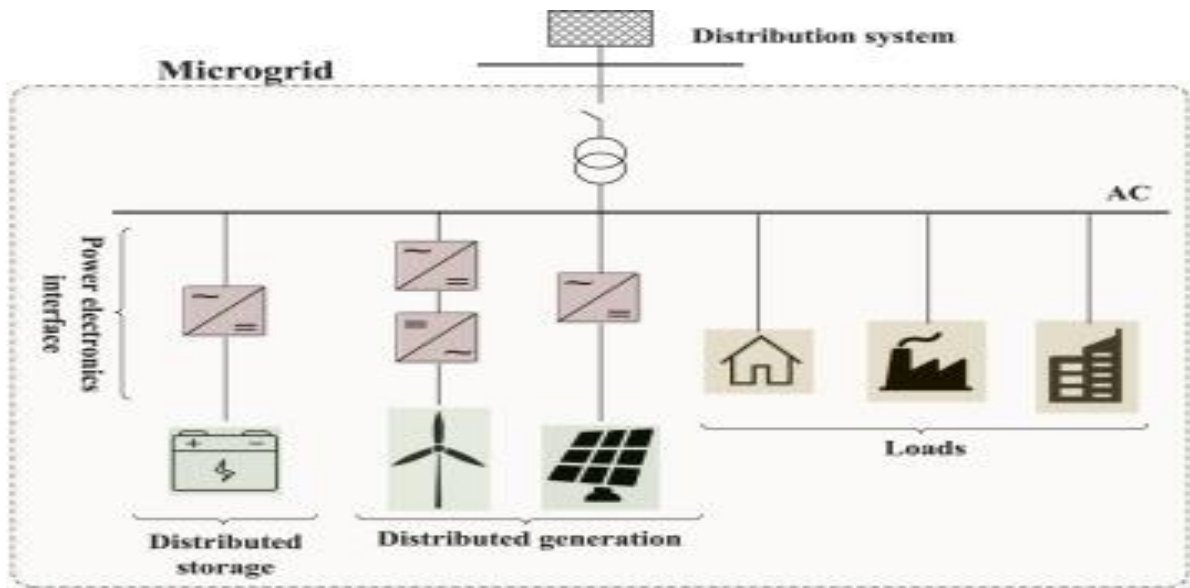


Figure 6-5: A simple microgrid connected to the distribution network[587]

From Figure 6-5, it is demonstrated that a microgrid can be connected to a distribution grid but can operate separately. They are therefore equipped with the main elements of the conventional grid i.e., the power electronics interface, power generation sources, energy storage, loads and own control systems. Therefore, a microgrid is a power system that generates electric power through a combination of both renewable and nonrenewable energy sources including.

A microgrid constitutes a group of interconnected loads and distributed energy resources operating as a controllable entity with respect to the electric power distribution grid. A microgrid has capacity to be connected or disconnected from the grid operation wise. Therefore, microgrids can be grid-connected systems or off-grid/island power systems[588]. The US department of Energy defines the Microgrid as a group of interconnected loads and distributed energy resources (DERs) possessing clearly defined electrical boundaries with ability to act as a single controllable entity with respect to the grid with capacity to connect and disconnect from the same grid [587, 589]. The use of microgrids can enhance the reliability and resilience to power grid to system disturbances. Based on geographical coverage, a microgrid is said to be a self-sufficient power system that can serve a discrete geographic footprint, for example a college campus, a military barracks, and medical hospital

complex. Therefore, microgrid constitutes a is a small-scale power grid that can either be operated independently or collaboratively with other small power grids[588]. Microgrids are designed to disconnect from the traditional grid and operate independently and locally. They can strengthen grid resilience and assist in mitigating the disturbances through their ability to operate even when the main grid is down and operated as a resource for faster system response and recovery in case of an outage. Microgrids support a flexible and efficient electricity grid through adapting to integrating more renewables and electric vehicles. Additionally, by using local sources of energy to serve local loads, transmission and distribution losses are reduced which increases system efficiency[590]. Advanced microgrids facilitate local power generation assets like renewable energy sources, traditional generators, fuel cells and energy storage to keep the local grid running even when the main grid is unavailable. Advanced microgrids also allow local assets to function as a unit and save costs, extend period of energy supplies, and generate revenue by energy market participation [586, 591].

Microgrids form a typical example of distributed, dispersed, decentralized, district or embedded power generation. A localized power station or small-scale station having its own generation and storage resources operating within definable boundaries is considered a microgrid. A hybrid microgrid is integrated with the an existing main power grid and is typically supported by generators and use renewable resources like wind and solar and are often used as a backup power supplementing the main grid supply during periods of high demand or curtailed supply by the main grid [2, 588]. A microgrid strategy which integrates local renewable energy resources can provide redundancy for essential services which makes the main power grid less susceptible to localized disaster. Facilities that are equipped with power generation infrastructure like solar panels and emergency generators can supply power and generate revenue, while connection to smart grid deployments, will enable the sale of power back to the local microgrids which provides system resilience and capacity to local electrical grids and generate revenues from power export [35, 360, 588].

Distributed energy systems like micro-grids in residential applications may not generate potential benefits due to lack of appropriate system configurations and suitable operation strategies. The design, scheduling and control of decentralised power systems is of great importance for successful practical realization [592]. The integration of decentralised generation load, energy storage and control devices to form a micro grid system and

presenting it to the power grid as a single and controlled unit can respond to centralized-control signals and coordinate the contradiction existing between the power grid and DG well. The main challenge at home is lack of uniform standards for micro grid communication which increases the difficulty in accessing the micro grid to the power distribution network [360, 593].

A micro grid is a power system designed to supply power to small communities or institutions with a local power generation unit. The micro grid connects both power generation and the utility grid and prevent outages [594]. A micro grid system is either grid-connected or standalone (Islanded) consisting of dispatchable distributed generators, non-dispatchable renewable energy resources, energy storage units, and controllable loads capable of load shedding. Grids connected micro grid can sell or buy power from the grid hence the need to optimise micro grid operation to manage the energy resources in a cost-efficient and sustainable way. A complete formulation for an optimum economic operation and scheduling problem of micro grids involves modelling BESS system, demand side management, and power exchange with the utility grid [586, 595].

A micro grid is also said to be a local energy grid with ability to control its components and can disconnect itself from the traditional grid and operate independently under circumstances like faults which is a boon in scenarios power outages caused by storms or other environmental conditions, and old which might otherwise lead to severe uncertainty in power generation and distribution[596, 597]. Micro grids are usually designed to integrate multiple sources of energy like solar photovoltaic, wind turbines, energy storage systems, and standby conventional sources like diesel generators locally, but with ability to exchange power with the macro-grid or other micro grids [598]. Micro grids are typically located close to load centres power which reduces transmission losses and the cost of installing power networks. The micro grids have increased resilience due to redundant distributed energy resources (DERs) incorporated in the micro grids. Micro grids are developed in several topologies and sizes to service a single facility or a vast area providing power to critical services and communities located far from utility systems [595, 596].

6.4.1. Application of Microgrids

Microgrids are generally small, power systems that are independently controlled operated in concert with, or apart from, the local distribution and transmission system. Microgrids can be powered by renewables, natural gas turbines, fuel cells, and small modular nuclear reactors. Microgrids can power critical facilities in case of outages on the main grid. Microgrids can be the main power sources for a hospital, university, or neighbourhood, the campus microgrids, industrial sites or military bases. Interest is growing in microgrids as many cities are now interested in power systems that can better integrate generation resources and load, meet environmental objectives, serve multiple users, and serve emergency response objectives. Fossil fuel-fired combined heat and power (CHP) and reciprocating engine generators have historically been used to power microgrids, but many microgrids are increasingly leveraging more sustainable energy sources like wind, solar power and energy storage [599].

Microgrids traditionally connect several businesses, building and other critical infrastructure with electricity which enable them to utilise multiple appliances and electronic systems. Although the users are interdependent, failure in one of the interconnected components may significantly affect other components and users in the system. This problem is solved by developing micro grids with ability to operate as standalone systems, whereas they remain typically connected to the main grid [596].

A micro grid is typically managed through a central controller that monitors the system parameters, coordinates energy resources, balances load and controls electrical loads, and disconnects and reconnects of the micro grid to the primary grid. Micro grids with no central controller are not common but are technically feasible, with distributed energy resource having an individual controller and the individual controllers operate in a coordinated manner. Micro grids can be an effective option to increase the energy resilience, by providing a functional electric power system capable of operating independently of the main grid. The main grid usually supplies primary power, while the micro grid provides secondary dispatchable power in the event of a grid failure. Emergency diesel generators can provide power directly to loads in the event failure of the primary grid and the micro grid.

Microgrids are attractive to users due to their ability to reduce possible risks and improve operational performance[596], and so they can be used by institutions to minimise energy cost, enhance reliability, and achieve energy sustainability. Since micro grids strategically

integrate renewable and non-renewable energy sources, variations due to weather conditions and time-of-the-day based availability concerns can be handled effectively [596, 600].

6.4.2. Role of microgrids in the energy transition

A microgrid is defined as a group of interconnected loads and distributed energy resources which operate as a single controllable system with respect to the main power grid with ability to connect and disconnect from the main power grid and operate as grid-connected or island mode. A microgrid is said to be smart and small-scale power system equipped with controllable loads, some energy storage system (ESS), and small generation units like renewable energy sources (RES, with ability to operate in islanded and grid-connected modes as allowed by the regulatory agency. Micro grids constitute the ultimate form of decentralized electricity, heat, and cold supply, with operations separated from the main distribution system as autonomous systems or connected to the distribution systems as grid-connected systems. Grid-connected micro grid can be of help during a system fault, by supplying power to the main distribution system, feeding part of its loads for fault detection and service restoration. Microgrids have ability to improve power system reliability and resilience to the grid disturbances. Since the transmission and distribution network are fully loaded for many grids, extra spending is needed on Transmission & Distribution expansion. However, use of the novel concept of microgrid using small generation resources dispersed throughout the power system primarily for back up can be synchronized to the grid power supply. Micro grids have emerged as a competitive alternative to the final delivery of energy to consumers in combination with on-site production of heat. Distributed generation grouped in micro grids can introduce a richer set of tools for supply of heat and power, at higher reliability, security, flexibility, and power quality in the conventional grid. A micro grid is typically managed through a central controller that monitors the system parameters, coordinates energy resources, balances load and controls electrical loads, and disconnects and reconnects of the micro grid to the primary grid. Microgrids can help deliver a sustainable and efficient power system by employing distributed or decentralised energy resources for efficient generation and supply local electricity load and increase the reliability of a local distribution network.

Proper design and planning of microgrids is important for them to yield all the advantages of the distributed energy concept for the power systems, both local and the clinked central power system. This calls for a reliability-oriented design for microgrids that utilise a

large share of the variable and intermittent renewable energy-based, and power electronics-interfaced distributed energy resources. Experience has shown that the power electronics used are prone to wear-out failure and can potentially have adverse effects on the performance of the entire power electronics dominated power system. Micro grids with no central controller are not common but are technically feasible, with distributed energy resource having an individual controller and the individual controllers operate in a coordinated manner.

A microgrid system has several protection and control devices which facilitate reliable, safe, and optimal operation like ability to connect with the public grid at the point of common coupling (PCC) and successfully operate in both islanded and grid connected mode. Other than solving extensive challenges of power supply in remote and critical installations, microgrids enable extensive use of renewable energy resources (RES) which helps in mitigation of greenhouse gas emissions. Generally, a single microgrid (MGs) is usually applied at a small scale or at the individual or community level, compared to smart grids (SGs) which are more complex systems covering much larger scale. Therefore, groups of interconnected microgrids can also be seen as a smart grid (SG).

Micro grids can be an effective option to increase the energy resilience, by providing a functional electric power system capable of operating independently of the main grid. The main grid usually supplies primary power, while the micro grid provides secondary dispatchable power in the event of a grid failure. Emergency diesel generators can provide power directly to loads in the event failure of the primary grid and the micro grid.

Microgrids have expanded in scale of operation, coverage, and penetration due to their significant benefits. The deployment of microgrids is however still facing challenges to efficiently design, control, and operate them both as off grid and islanded systems hence the need for extensive research activities. As a result of the need to have an across-the-board view of the microgrid integration in power systems, this study presented a review of issues concerning microgrids and identified various aspects of microgrids including their role in distributed generation, microgrid value propositions, the applications of power electronics, and other system elements, microgrid benefits and limitations and areas for further research.

Microgrids provide benefits to the environment, the power system, and energy customers by facilitating the deployment of greater quantities of low-emission energy sources, thus creating opportunities for higher efficiency, and enable system reliability and benefit the customers and their surrounding communities. Because of increasing interest in related “smart city” investments, renewable energy, and resilience measures, further investment and adoption of the potential of microgrid concept needs more awareness and incentives for them to fit into the electricity grid of the future by addressing the legal uncertainties, provide for financing plans, technology development by creating development incentives, removing policy barriers, and establishing demonstration microgrid projects.

6.5. Virtual Power Plants

A virtual power plant (VPP) refers to a combination of different distributed energy resources (DERs). A virtual power is a decentralized energy resource system consisting of many small-scale DERs like solar energy, wind energy, CHPs, fuel cells, and plug-in hybrid electric vehicles (PHEVs) operating in a single energy monitoring profile, while considering different parameters characterizing each distributed energy source. A VPP can supply reliable and cost-effective energy to customers. A large-scale VPP is formed with a combination of different small-scale VPPs. The two main types of virtual power plants, are commercial and technical [601].

A virtual power plant is a network of decentralized power generating units like wind farms, solar parks, combined heat, and power (CHP) units, and flexible power consumers and storage systems. That are interconnected and dispatched through the central control room of the VPP while remaining independent in their operation and ownership. The main objective of the virtual power plants is to relieve the load on the grid by smartly distributing the power generated by the individual units during periods of peak load. These interconnected units can additionally, trade on the energy exchange [602].

Virtual power plants can accomplish a whole range of tasks which depend on the market environment. The objective of a virtual power plant is to network distributed energy like wind farms, solar parks, and Combined Heat and Power (CHP) units, to enable monitoring, forecasting, optimization, and trade of the power. By so doing, fluctuations in the generation of renewables are easily balanced by ramping up and down power generation and power

consumption of controllable units[603]. This stabilizes the power grids and creates preconditions for integrating renewable energies into the power systems. The generation profile of small units varies too strongly or they simply do not meet the minimum bid size of the markets thus by aggregating the power of several units, virtual power plants can deliver the same service and redundancy and subsequently trade on the same markets as large central power plants or industrial consumers [603].

6.6. Energy Storage

The content of this section on energy storage is published in papers [604], co-authored by Prof. Oludolapo. Energy storage systems play an important role in improving the reliability of electricity networks due to increasing contribution of electricity from intermittent sources like wind and solar. The main considerations in choosing a suitable storage system are cost and performance. Since the price for every kWh supplied to the network and battery energy storage system (BESS) costs are dynamic, consumers interested in a battery may have challenges in choosing between the various batteries available in the market. The future power plants are expected to have large proportions of intermittent energy sources like. wind, solar or tidal energy that require scale-up of energy storage to match the supply with hourly, daily, and seasonal electricity demand profiles. Available storage technologies include batteries, pumped hydroelectricity storage, compressed air energy storage and power-to-Gas storage. The energy transition to renewable energy supply calls for increased application of energy storage. Identification of optimal solutions requires a holistic view of the energy system beyond the electricity-only focus. In this study, an integrated cross-sector approach is adopted to identify the most efficient and least-cost storage options for off grid and grid scale application. Storage batteries can widely be divided into solid state batteries and flow batteries using solid and liquid electrolytes respectively.

Electricity is a dominant form of energy but limited by variations in instantaneous demand daily and seasonally. Energy storage is useful in balancing the demand and supply of electric power. The grid-level large-scale electrical energy storage (GLEES) is a process used to convert energy from a grid-scale power network into a storable form for later conversion to electricity [318]. Many battery chemistries are either available or under investigation for grid-scale storage applications. They include lithium-ion, lead-acid, redox flow, and molten

salt (including sodium-based chemistries. The use of utility-scale battery storage makes power systems more responsive to fluctuations in demand and supply and more flexible. Batteries support greater integration of variable renewable sources of energy to the grid, by storing energy from variable sources like solar and wind for later use. There is growing need for more flexible power systems to ensure more variable renewable sources are integrated efficiently and reliably. The battery storage systems have emerged as a potential solution to improve power system flexibility because of their ability to quickly absorb, hold and then reinject electricity. Utility-scale battery storage systems' capacity ranges from a few megawatt-hours (MWh) to hundreds of MWh. Different battery storage technologies like lithium-ion (Li-ion), sodium Sulphur and lead acid batteries, can be used for grid applications. Recent years have seen most of the market growth dominated by in Li-ion batteries [321, 322]. The global increase in use of small-scale and distributed generation, and use of variable renewable have led to high demand for electrical energy storage systems (ESS), which applies different storage device. They include electrochemical storages, super capacitors, gravity batteries etc. The challenge is that we have no universally accepted economic indicator which for use in comparing compare different energy storage systems unlike in power plant planning where "Levelized Cost of Electricity (LCOE)" has been accepted [323]. Combining storage and renewable in a power system improves flexibility, which promotes adoption of renewable energy by ensuring security of the power grid. The future energy systems dominated by renewable energy will require largescale and wide application of energy storage technologies [324].

The main cause of growing use of energy storage is interest in small-scale and distributed generation, and use of renewable energy sources. There is however no generally accepted economic indicator for comparison of different energy storage systems, unlike in the planning of power plants which mainly use the "Levelized Cost of Electricity (LCOE)" which has now been modified. for application in electrical energy storage systems, this derived indicator is called "Levelized Cost of Storage (LCOS)". However, the LCOS calculation procedure is not yet approved but its popularity has been growing [605]. Levelized cost (LCOS) quantifies discounted cost per unit of power discharged for a given storage technology and application. Therefore, the Levelized cost of energy is used to account for the technical and economic parameters that affect the lifetime cost of discharging stored electricity. Levelized cost of

storage is equivalent to Levelized cost of electricity (LCOE) for generation technologies, but represents an appropriate tool used for comparing the costs of storage technologies[369].

6.7. Cogeneration and Trigeneration

Cogeneration is also called combined heat and power (CHP) generation of heat and electricity at the same time from the same fuel source. In combined heat and power (CHP) plants, waste heat is recovered and put to useful use for thermal applications like heating which in this case is referred to as combined heat and power district heating. Waste heat recovered can also be used in absorption refrigerators for cooling applications[334]. In cogeneration systems, the heat energy may be used to generate steam, hot air for dryers or chilled water for process cooling. With over 60% of fuel energy being lost to exhaust and cooling systems, cogeneration is an attractive measure to improve an engines overall thermal efficiency [606]. Cogeneration, otherwise known as combined heat and power is simultaneous generation of heat and electricity from the same energy source. Cogeneration has become a leading option in energy generation and use where both heat and electricity are required. In 2010, Denmark produced 63% its electricity generated from thermal sources was produced through combined heat and power (CHP) plants. Cogeneration generates both heat and electricity simultaneously leading to higher total efficiencies than dedicated heat and power plants, which leads to reduction in overall costs, less fuel consumption, and less emissions. The overall efficiency of newly installed CHP systems in the European Union generally varies between 60% to 90% while electrical efficiency of between 30–55% [279]

6.7.2. Types of Cogenerations

Based on usage, cogeneration can be classified into three types, namely

6.7.2.1. Industrial Cogeneration

Industrial cogeneration is applied in industries that require both heat and electrical energy. These industries use the dual demand opportunity to generate steam in boilers for generation of electricity and heat for own consumption and they can export the excess of these forms of energy [567]. In some cases, a plant may need coolness in addition to heat and electricity which leads to trigeneration by installation absorption chillers. A typical example of industrial cogeneration is the sugarcane industry where sugarcane factories use bagasse to generate steam in boilers to run steam turbines for power generation with the exhaust steam being used

for process heating[81, 192]. Another example is of industrial cogeneration is a modern sewage plant which produce biogas for process heating purpose and generation of electricity for use and export[607, 608].

6.7.2.2. Heating Cogeneration.

Heating cogeneration is applied where there is substantial demand for heat which is the main product of interest but in the process, some generation of electricity is done as a by-product. An example of this is district heating systems which usually produce heat at temperatures between 40°C and 140°C.

6.7.2.3. Agricultural Cogeneration

This cogeneration is used mainly in rural processes like agriculture which need heat of between 15°C and 40°C for processes like cereals drying and horticulture in green houses. Agricultural cogeneration systems aim at producing useful heat and in the process generate electricity for own use and sell of excess[567]. Cogeneration cycles can be classified as topping cycle plants or bottoming cycle plants. Topping cycle plants have a primary objective of producing electricity from a steam turbine and the exhaust steam or partly expanded steam then used for heating at appropriate temperature and state for use in district heating, water desalination and other thermal applications. Bottoming cogeneration cycles produce high temperature heat for process use and then the waste is recovered in waste heat recovery boiler to generate steam for power generation. The Bottoming cycle plants are found in high temperature industrial processes like furnaces for glass and metal manufacturing.

6.7.2.4. Steam Turbines-Based Cogeneration

Steam turbine cogeneration systems work on the Rankine's cycle and are quite flexible when it comes to fuel used. There are two types of steam turbines used in cogeneration. The turbines used are the Back-Pressure Turbine and extraction condensing turbine. In back pressure turbines, steam exits the turbine at its exhaust at a pressure higher than atmospheric for process use. In Extraction-Condensing Turbines, process steam is extracted at a pressure higher than exhaust pressure between the turbine stages while the unextracted steam is allowed to expand through to the turbine exhaust into the condenser. Although back pressure turbines are simple in construction and cheaper than the extraction-condensing steam turbine type, they are less efficient and hence generate less power than the condensing type [81, 567].

6.7.2.5. Gas Turbine Cogeneration System

This cogeneration system is applied on gas turbine plants where the turbine exhaust which has high energy content is used for thermal applications[567]. The system can also be used to generate extra power by means of a steam turbine by using the turbine exhaust gases to generate steam for the Rankine cycle turbine. Cogeneration can be applied on the steam turbine using the two modes i.e., back pressure system or the extraction-condensing turbine. In some cases, only electricity is needed, so a pure condensing turbine is the best option for maximum power generation[81, 114].

6.7.2.6. Recuperating Engine Cogeneration System (RECS)

This system uses an internal combustion engine to provide mechanical power and heat at a higher efficiency than in steam and gas turbines systems. In recuperating engine cogeneration system (RECS), heat is recovered from four sources, namely the exhaust gasses, lubrication oil, the engine jacket-cooling water and turbocharger cooling systems. Recuperating engine cogeneration system is an ideal cogeneration system for off-grid, low and medium power systems, and distributed generation systems. The advantage of RECS is that it is flexible and is quick to stop and start hence ideal as a standby unit. However, it is expensive to maintain[567].

6.8. Electrification of Transport

The content of this section on transport electrification is published in paper [35] co-authored by Prof. Oludolapo. It is possible to reduce emissions faster in electricity systems than many other systems because as in 2019, about 37% of global electricity generation came from low-carbon sources i.e. renewables and nuclear energy with the rest coming from coal and other fossil fuel sources[123]. Phasing out coal fired power plants is among the easiest and fastest ways to controlling greenhouse gas emissions and in its place increase the share of renewable and low carbon electricity generation[609]. A leading limitation in provision of universal access to electric power is rural electrification where both off-grid and on-grid systems based on renewable energy can power villages who predominantly rely on wood fuel, kerosene and diesel generators for heat lighting and power. ^[154] Wider access to reliable electricity would lead to less use of kerosene lighting particularly for the developing countries[610].

Electrification of transport is significant because transport sector accounts for about 14% of global greenhouse gas emissions which can be reduced by use of electric cars, buses and electric trains that consume green electricity[611]. The various climate change scenarios predict extensive electrification and substitution of direct fossil fuel combustion with clean electricity for heating building and for transport. A deliberate climate policy should see double increase in energy share from electric power by 2015 from the 20% of the year 2020[26, 123, 610].

6.9. Demand Side Management and Demand Response

The content of this section on demand side management is presented in journal paper [16]. Demand reduction is a key option in the design of energy supply schemes, aimed at balancing the energy demand with available supply, instead of developing new facilities to cater to increasing demand. Demand Side Management (DSM) refers to a set of activities, applied to encourage energy consumers to modify their level and pattern of energy use. Strategies in demand side management include energy reduction and load shifting, peak shaving etc. which alter the load profiles to constant flat load curves which allow more electricity to be provided by less expensive base load generation. The initiatives avoid peak demand burden on the network by supporting efficient utilization of available generating options. Hence demand reduction and demand side management are important in the foreseeable future [252].

The evolution of the energy management system (EMS) started in the 1960s, and was termed a control center, and later was referred to as an energy control center (ECC) during the 1970s. It was renamed supervisory control and data acquisition-EMS (SCADA-EMS) when the SCADA system which works based on advanced computer appeared in the 1990s. This later evolved into a real time control system known as energy management system (EMS). The EMS incorporates various control techniques like load control (LC), demand supply management (DSM), and distribution management system (DMS). The role of the EMS is to allocate energy to the customers optimally while integrating sustainable power sources without compromising power system security, reliability, and safety. The energy management system monitors, supervises, optimizes, and controls the generation, transmission, distribution, and consumption of energy to create a balance demand and supply for cost efficiency while

maintaining the operational constraints and uncertainties on EMS architecture including variability and intermittence of renewable energy sources, price of electricity and customer behaviors[315, 612].

The energy management system can work for real-time SCADA applications, electricity dispatch, generation scheduling, system control, and energy accounting and energy transmission security management. Today and into the future, energy management systems are becoming more and more complicated, because of growing use of plug-in electric vehicle (PEV) and variable renewable sources (VREs), energy storage systems (ESS), growing energy demand in buildings and industry among others. The functionalities of the energy management system has further been enhanced by advances in the internet of things (IoT) and machine learning and their adoption by the energy sector [315].

The growing integration of highly varying or fluctuating distributed generations systems particularly PVs, wind t, electric vehicles, and energy storage systems is a serious threat to the stability of power systems because balancing power ratio between supply and demand becomes difficult and complicated. Excess or shortage in the generation or consumption electricity causes perturbations to the grid and create severe issues like voltage drop or voltage rise and related blackouts. Under such threats, the energy management system is adopted to ensure efficient balancing between power supply and consumption demand to reduce the peak loads when undesirable[613, 614].

The energy management is divided into two main categories, namely the supplier side like electric utility, where some generators may be switched ON or OFF or follow the fluctuation of demand (demand following). In the second category is the consumer side, or demand-side management, where the consumers manage their energy consumption to match supply from power generation side. On the consumer side, the main goal of the energy management system is to reduce operation cost as well as consumption, reduce energy losses and enhance power system reliability. The development of sophisticated algorithms and models will improve the energy management systems[613, 614].

Energy Management System (EMS) is used by grid operators as a tool for monitoring, controlling and optimization of power generation and transmission systems. The main functions of the energy management system include real time network analysis and

contingency analysis, Study power flow, power factor, security enhancement. The EMS enables real-time functions which the plant operator to monitor, analyze and control power generation functions on a real time basis. It also enables automatic generation control. The energy management system also sets economic dispatch and directs the dispatcher to set economic base point for the generator units selected.

Other functions performed by the energy management system of the smart grids include monitoring of the reserve and establishing spinning reserve, regulating reserve and operating reserve levels. The energy management system also computes the production costs, forecasts load, schedules transactions. The smart grids advanced functionalities include grid reliability enhancement, increasing grid capacity, advanced contingency awareness operations and cost management. Besides the technical capacity and requirements, a smart grid should meet the regulatory requirements[566]. Therefore, overall energy management system in a smart grid enhances reliability, increases efficiency and compliance with standards.

Various bioinspired approaches are used for smart Energy Management Systems strategies with commonly used systems being the Home Energy Management Systems (HEMS) and Building Energy Management Systems (BEMS). There are two groups of bioinspired Bio-inspired computing, i.e. evolutionary computing and swarm intelligence computing[69]. Evolutionary computing involves the incremental development of living organisms in reaction to environmental conditions, while swarm intelligence focuses on agents' collective and social behaviors in the energy system. These algorithms assist in the design, planning, and control for smart energy management systems for homes, buildings, and smart grids [615]. The main objective of the energy management system in a smart grid system is to minimize energy consumption by device scheduling within specified time horizons [103]. The main functions of the energy management system are summarized in Figure 6-6.

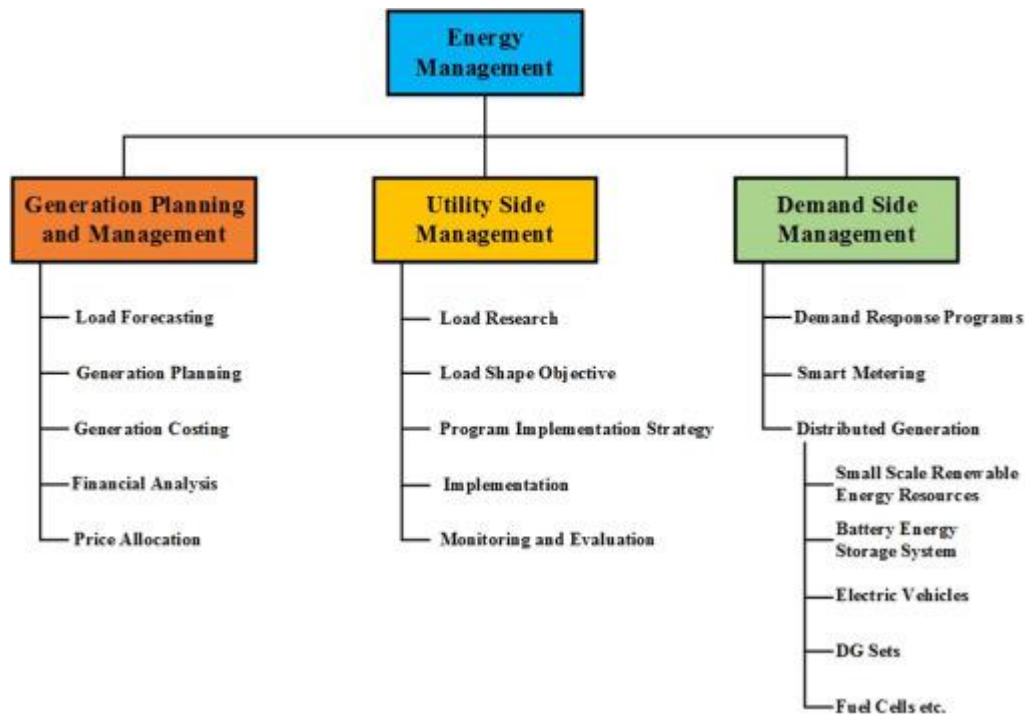


Figure 6-6: Functional view of energy management system in a smart grid.

From, it is noted that the energy management system in a smart grid has three main functions, namely demand side management, utility side management and generation planning and management.

The planning and execution of grid activities must be done by means of interoperability. The National Institute of Standards and Technology (NIST) established the smart grid interoperability (SGIP) whose responsibility was to develop and maintain the standards for smart grids and related components necessary for efficient operation. SGIP also provides a platform for all the stakeholders of power grid like the markets, customers, service providers, the power system, generation, transmission, and distribution network to cooperate and work together. Grids and end users must play their roles effectively for implementation of energy management. The energy management system is made more realistic for smart grids due to technologies like communication ,advanced metering infrastructure (AMI) and cyber security which facilitate self-decision capabilities for the power grid[97]

6.10. Smart Meters and Advanced Metering Infrastructure (AMI)

Smart metering can revolutionize access and control of energy consumption. A meter is said to be smart if it has capabilities like real-time monitoring; local and remote data accessibility;

remote meter controllability, energy cut off; interaction with other meters like gas meters, water meters; quality monitoring of power and device self-analysis; and interaction with the internet of things (IoTs) [616]. In studies on ICT linked energy saving by [616, 617] it was estimated that between 0.23 and 3.3% of the European CO₂ reduction target to reduce global warming to the 1.5 °C minimal realistic warming goal by 2100 can be attributed to the use of ICT in the energy sector. Smart meters make it possible to read in real time rates and pricing policies, which facilitate demand response and demand side management programs. Hence smart meters enable realization of energy efficiency, increase system reliability, and yield significant economic savings to both customers and utilities. [616, 617]. Smart meters constitute an important element of the smart metering system.

Advanced Metering Infrastructure (AMI) is also called Smart Metering and comprises of equipment or devices like Smart Meters, Data Concentrator Units (DCUs) also referred to as gateways, routers or access points, Meter Data Management System (MDMS), Home Area Network (HAN), Head End System (HES), communicating over bi-directional Wide Area Network (WAN), Neighborhood Area Network (NAN) or Field Area Network (FAN) and Multiple smart meters used to connect to the DCU/gateway/router/access point to send aggregated data to the head end system (HES). Smart meters can communicate with the HES directly via appropriate wide area networks (WAN) technologies like the GPRS sim cards placed in the smart meters to send data to head end systems (HES) on the servers in the control room[566].

The role of the MDMS (The Meter Data Management System) is to collect data from the head end system (HES), process and share with the billing system as well as other information technology (IT) applications. The home area network (HAN) can incorporate common appliances like fridges, television sets, radios, heaters, dryers, washing machines, air conditioners, water heaters among others. It is the inclusion of a two-way machine to machine (M2M) communication module in a meter as well as a remotely operated connect and disconnect switch that makes a meter smart. The smart meter is always at the heart of the advanced metering infrastructure (AMI). The smart meter electronically records electricity consumption normally on hourly intervals or less and communicates with the utility on regular basis for monitoring and billing. Smart meters facilitate a two-way communication between computer systems/computers at the utility control centers and the meter[618]. They are

equipped with real-time or near real-time sensors, power quality monitoring features and outage notification capabilities[566]. This capability helps in cutting down outages through quick response in case power failure or intermittent in supply where supply comes from variable renewables or outages caused by extraneous factors to the conventional power supply sources.

Smart meters are the backbone in the development of smart grids. smart meters make billing free from manual intervention unlike the traditional billing system where an individual must move from house to house to note down the readings from energy meters normally once a month. With smart meters, billing can be done for multiple consumers any time desired[618].

6.11. Demand Side Management

There are several benefits of demand side management which range widely from economic, environmental, and technical like reliability. Demand side management leads to cost reduction, alleviates electrical system emergencies, reduces outages or blackouts, enhances power system reliability, and delays or defers capital investment in capacity expansion and delays expansion in transmission and distribution network capacity[3].

To achieve efficient load management in demand side management (DSM), the following measures are encouraged:

- i. Promote the use of energy-efficient products and equipment e.g. more efficient lighting technologies,
- ii. Sensitize customers and encourage them to shift non-critical power consumption from peak hours to off peak.
- iii. Encourage construction of high efficiency buildings, and
- iv. Create energy awareness and education.

Therefore, deployment of demand side management treats consumers like virtual power plants because they actively participate in stabilization of the grid by planning and monitoring their activities, as they are compensated for lowering, shifting, or modifying energy consumption. Successful implementation of DSM depends on the ratio of controllable loads to the total system load in the grid. Development and adoption of new types of electric equipment and technology like use of plug-in hybrid electric vehicles (PHEV) enhances the ratio of controllable loads hence demand side management. Energy storage in PHEVs enable the

storage of electricity and use during peak hours, thus making PHEVs important components of demand side management (DSM) as a tool for balancing power supply and demand in smart grids and microgrids [3, 587].

6.12. Behind The Meter Management

The fast-growing energy needs globally have intensified a central challenge in terms of how to reduce costs in generation and operation for power systems and, minimize the carbon emissions. With about 25% mankind still lacking access to electricity, and cost of building conventional power grids remain high for many countries. The behind-the-meter (BTM) energy systems offer cost-effective solutions the challenges of high costs of power to end-users who can satisfy their energy needs with distributed energy generation and storage technologies [619].

The power grid operations have become more stressed as a result of growing customer demand and increasing integration of intermittent renewable resources amid growing concerns over emissions from usage of fossil fuels in the electricity generation particularly during the peak hours. One effective solution to this challenges is the deployment of smart energy management systems to integrate communication, control, and sensing technologies to shape the electricity consumption efficiently [619].

The term behind the meter (BTM) refers to renewable energy system located in a single building or at multiple facilities but owned by a single entity usually operated with distributed generation and storage units to supply all or some portion of the energy demand . The critical part of BTM system is orchestration of loads through efficient optimization and scheduling algorithms. Behind the meter (BTM) systems are not connected to the bulk generation, instead are connected to end user's meter to enable export of energy back to the utility. Therefore, behind the meter energy management systems is a system which meets the end users energy needs while reducing operation cost, improving energy efficiency, balancing demand and supply, and reducing carbon emissions[619]. Figure 6-7 illustrates the behind the meter (BTM) system.

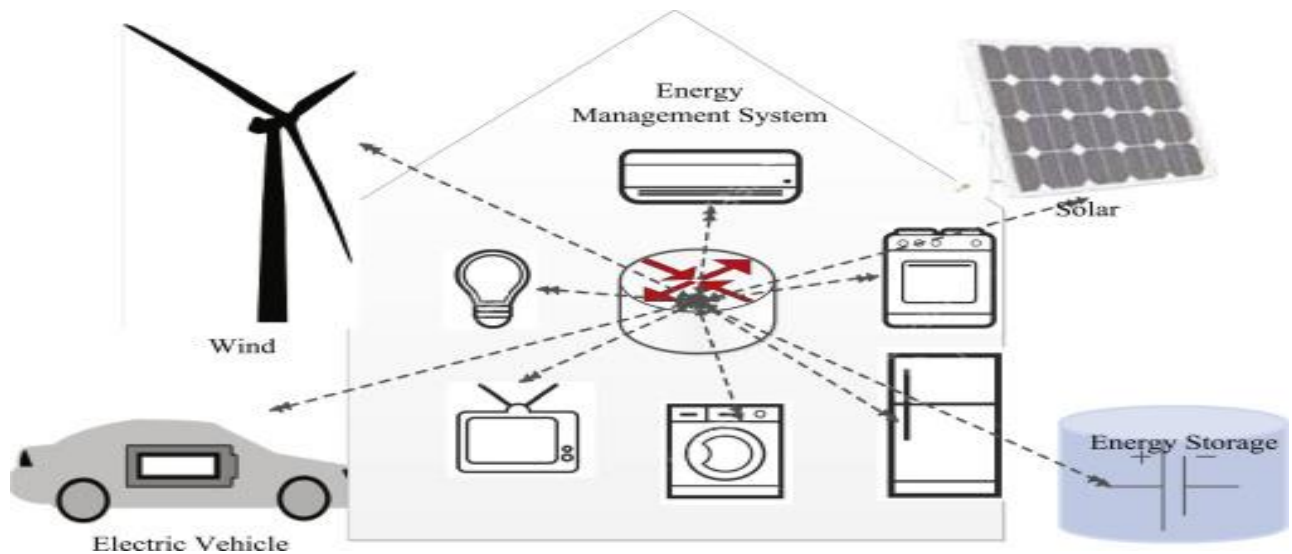


Figure 6-7: Behind the meter system: case for single household[619].

From Figure 6-7., it is noted that important elements of the BMT system are energy storage, renewable energy sources i.e. wind, solar and the energy management system (EMS).

6.12.2. Benefits

The multifaceted benefits of the BTM energy management systems are associated with to the current power system operations. Largescale energy storage is still evolving making it necessary to align demand and supply on real-time basis. Hence utility operators dispatch generation assets based on cost, flexibility, environmental impact and distance to load. The traditional approach by power system operators is to plan the system capacity i.e. generation portfolio, transmission capacity, transformer ratings based on projected peak energy demand plus additional reserve margin typically set as 15%. This approach provides reliability but leads to inefficient use of resources because peak generation typically occurs only around 10–12% of the time [619]. Therefore, the use of energy management systems reduces usage of dispatchable peak generators leading to the following benefits.

i. Economic Benefits

With about 40% of the residential energy being wasted due to lack of awareness, promoting customer-utility interaction, will enable users to enjoy incentives and differentiated tariffs for shifting peak load demand and enable them to make a profit by selling excess power to the grid, while utilities and regulators benefit from increased utilization of grid components and reduction in new generation investments. By demand-shaping with energy storage units,

consumers make monetary savings under different scenarios like varying utility tariffs, and consumption patterns.

ii. Reduced Green House Gas (GHG) Emissions:

The power generation sector accounts for over 40% of the global greenhouse gas emissions and with commitment and increased use of locally available renewable sources in decentralized generation, behind the meter is an emission reducing strategy. Consequently, nations with high carbon-intensity put bold renewable integration targets. [619].

iii. Deferred Grid Investments

The BTM energy management systems seek to reduce the stress on the grid leading to postponement of the required upgrades to supply peak demand and stagger it gradually over a longer time. The resulting deferral enables utilities to avoid exhaustive sitting processes. With over 1.3 billion people globally having no access to electricity, BTM systems is an attractive option for remote locations like farms, villages, and off grid consumers.

iv. Improved Grid Resiliency and Power Quality

By adopting distribution generation and storage technologies combined with intelligent energy management tools, power service interruption will reduce significantly and protect loads against short-term adverse effects like voltage spikes, dips, and power surges and hence guarantee quality power supply. With BTM management locally generated energy user demand can be supplied locally and reduce the need for far-off high-capacity generator options. This minimizes congestion on transmission lines and associated lines. Monetary savings will be realized with storage units and their efficient control[619].

v. Energy Independence and Security

The promotion of distributed generation and enhanced efficiency with BTM energy management systems enhances energy security and independence due to higher consumption of domestic resources which reduces the dependency on foreign or important energy resources. Because of the various benefits discussed, regulators and policymakers, and specific targets have been cutting down energy consumption.

6.12.3.Components of Before the Meter (BTM)

The main components of the BTM are the loads used by consumers which are classified based on their physical properties like the resistive, inductive, and conductive, job types i.e.

essential, deferrable, throttleable, flexibility, and the size of the loads e.g., home, microgrids, etc.[619]..

Behind the meter energy management can be classified into three partially overlapping layers i.e., technology, economic and social layers.

i. The Technology Layer I

The technology layer includes technical components and systems like distributed generation, storage technologies and their efficient operation, their management, and control. Since adding new production and storage capacity is very expensive[619].

ii. Economic layer

This layer is concerned with economic incentives employed to influence and shape energy consumption and related emissions. The subjects and topics in the economic layer include optimization, scheduling, and control of appliances with technology level components acting as constraints in the problem statement of the economic layer. [619].

iii. Social Layer

The social layer attempts to understand the role of human behavior in energy consumption and how to control human behavior. It is the , the technology layer that controls the system capacity since it depends on the output of the renewable generation and the state-of-charge level of the storage unit while the economic and the social layers match the consumption with the system output by controlling and scheduling load[619]..

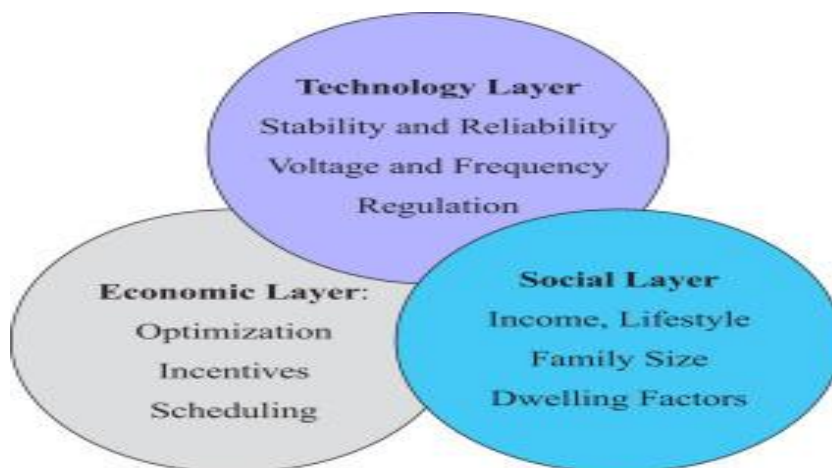


Figure 6-8: Three domains determine the operation, control, and management of behind the meter energy management systems.

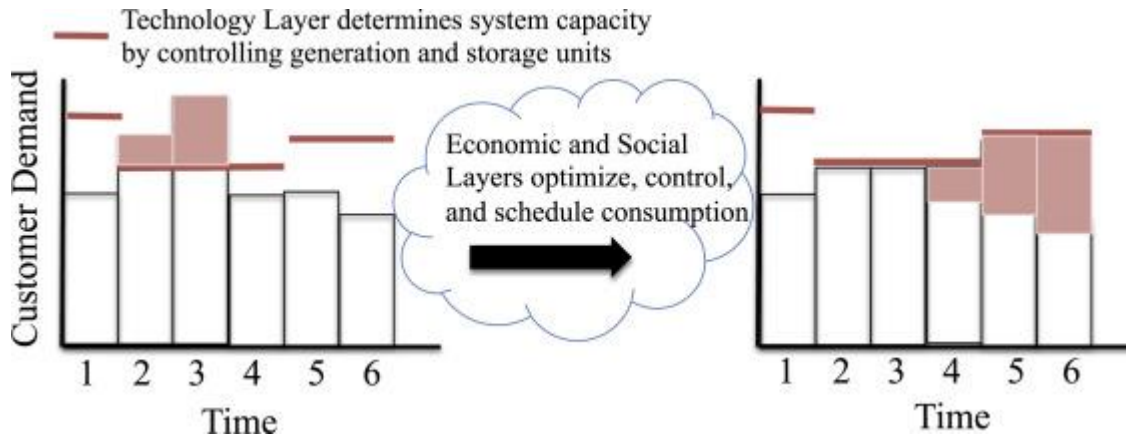


Figure 6-9: Illustration of three-layered approach.

It has been proposed by the scientific community that energy management for behind the meter systems needs interdisciplinary research efforts ranging from power systems, optimization, communications, control, economics, and sociology. The challenges and opportunities of BTM systems can be analyzed based on technological, economic, and social layers. [619].

6.13. Shift From Diesel and Coal Power Generation to Natural Gas and Biomethane

Diesel power plants use diesel engines as prime movers powered mainly by heavy fuel oil or industrial diesel oil and with potential for conversion to gas engines or dual fuel engines which use natural gas or biomethane. The global concerns over prices of diesel and heavy fuel oil and energy related greenhouse gas emissions have created demand for natural gas as an alternative fuel for power generation by diesel power stations. Coal on the other hand represents the most polluting of the fossil fuels.[93, 280]

The growing global concerns over high cost of diesel and heavy fuel oil have generated the immense desire for alternative energy sources like natural gas whose use is less polluting and is cheaper. The internal combustion engines have wide applications as prime movers in power generation and transport industries. Compared to petrol engines, the diesel engines have higher thermal efficiency and higher power density making them ideal for heavy commercial and

power generation applications. Diesel engines have significant variation in size but generally vary between 10 hp and 140 hp. For diesel power plants, the electric generators are driven by diesel engines as prime movers. Diesel engines are attractive prime movers because high part load and full load thermal efficiency, ability to start quickly and ability to run on a wide range of fuels including biofuels[280].

The main limitations of diesel power plants are high cost of power generation and high environmental impact due to high level of total greenhouse gas emissions in form of nitrogen oxides (NO_x), particulate matter (PM), carbon dioxide (CO₂) and sulfur dioxide (SO₂) [93]. As a result of these concerns, there is globally growing shift to cheaper and cleaner fuels for diesel power plants and other diesel engine applications because of concerns over changing global climate, strict environmental regulations in some jurisdictions, high cost of diesel power generation especially for non-oil producing countries and general sustainability concerns. As the global community continues with its search for alternative and renewable fuels, natural gas has presented itself as a cleaner alternative fuel for the diesel power plants during the transition . Natural gas is cheaper and is widely available as a fuel for power plants making diesel power generation cheaper, cleaner, and more reliable. A shift from diesel to natural gas as fuel for engines will reduce total emissions and unit cost of power[280].

Natural gas is a naturally occurring cleaner fossil fuel compared to other fossil fuels like oil and coal. Natural gas is cheaper and widely available globally and with possibility of substitution with biomethane which is regarded as renewable natural gas. The main elements or constituents of natural gas are methane (CH₄), nitrogen, ethane, propane, helium, hydrogen sulphide water vapor, and carbon oxide and water vapor. The energy content is influenced by the composition of methane, while hydrogen sulphide is destructive to the engine parts. The various design modes of natural gas-powered engines are spark-ignition engines, pure gas engines, dual fuel, and bi-fuel engines. Natural gas is an attractive engine fuel mainly because of environmental friendliness, easy substitution with petrol in spark ignition engines due to high octane rating, low operation and maintenance costs, and low price and high combustion efficiency compared to other fossil fuel[280]

A normal diesel engine can be converted to dual fuel (which runs on both diesel and gas) but for this to happen, several modifications must be made to the engine and engine systems.

Modifications will enable the engine to handle gas and diesel simultaneously. The fuel must be mixed in the right ratio with diesel oil being used as a pilot oil to initiate combustion. The compression ratio has to be reduced while the fuel injector nozzle should match the desired flow rate and injection pressure. A standard diesel engine can be changed to a dedicated gas engine or dual fuel engine, both of which require different degrees of modification. The engine modification includes removal of the injector pump and injection nozzles which serves as the diesel fuel for the conventional engine.

The reduction in the compression ratio can be achieved through methods like machining off some piston material; installation of power supply for the alternator from the battery to run the stator and power the ignition system for the gas; provision of the fuel mixer which mixes and supply the air fuel mixture as a venturi-mixture. Regulation of fuel supply also regulates the engine operation.; mounting of the ignition system with a distributor together with the ignition coil and spark plugs [280].

An important requirement for dual fuel and gas engine operation is the reduction in the compression ratio which can be realized by various means. The methods applied include replacement of pistons to achieve lower compression, cutting off part of piston material to increase clearance volume or replacing the cylinder head with a one with different parameters or replacing the cylinder head gasket with a thicker one [280].

6.14. Carbon Capture and Sequestration

Carbon capture and sequestration (CCS) is a viable mitigation strategy for reducing greenhouse gas (GHG) emissions in fossil-fuel power plants and discusses the impacts on the sustainability of freshwater resources. While CCS technology can significantly mitigate anthropogenic GHG emissions, CCS installations are expected to impose new water stresses due to additional water requirements for chemical and physical processes to capture and separate CO₂. In addition to these processes, the parasitic loads imposed by carbon capture on power plants will reduce their efficiency and thus require more water for cooling the plant. Groundwater contamination due to CO₂ leakage during geologic sequestration is an additional concern when adapting CCS into power plants. Imposing such constraints on the quantity and quality of freshwater resources will influence decisions on the types of energy facilities and threaten the sustainability of water systems.

All emission pathways seeking to limit the global warming to 1.5 °C or 2 °C by the year 2100 assume the use of CDR approaches in combination with emission reduction. There are two main strategies for removing carbon directly from the atmosphere i.e., by planting and forest restoration, which is referred to as conservation efforts, and by direct air capture (DAC). Carbon dioxide removal (CDR) which is also known as negative CO₂ emissions, involves the removal of carbon dioxide gas (CO₂) from the atmosphere and storing in geological, terrestrial, or ocean reservoirs, or in products.

6.15. CDR

Carbon dioxide removal (CDR) refers to anthropogenic activities that remove CO₂ from the atmosphere and store it in geological, terrestrial, or ocean reservoirs, or in products. They include existing and potential anthropogenic enhancement of biological or geochemical sinks as well as direct capture from air and storage. This however does not include natural CO₂ uptake not directly caused by human activities. Similar definitions are commonly used for "net negative greenhouse gas emissions", "net zero CO₂ emissions" and "net zero greenhouse gas emissions". Geoengineering or climate engineering is used for both CDR or SRM (solar radiation management, if used at a global scale, but they are no longer used in IPCC reports.

Greenhouse gas removal (GGR) or negative greenhouse gas emissions refers to the removal of greenhouse gases (GHGs) from the atmosphere through human activities, which is in addition to what occurs via natural carbon cycle or atmospheric chemistry processes. Within the context of net zero greenhouse gas emissions targets, carbon dioxide removal (CDR) is increasingly integrated into climate policy new element of mitigation strategies. Both CDR and GGR methods are referred to as negative emissions technologies (NET), and may be cheaper than preventing some agricultural greenhouse gas emissions[620]. Carbon capture and sequestration being a very important sustainability measure is discussed further in chapter 12

6.16. Emerging or Developing Waste Heat Recovery Technologies

There are various technologies being developed and tested at the laboratory or pilot scale in many different countries to be used in waste heat recovery. The status of the technology or product development depends on the local energy situation in terms of cost and availability or access as well as availability of support from the local governments or funding agencies. The,

the following emerging WHR research topics and technologies are under investigation in many countries.

- i. Conversion of waste heat into a flexible and transportable energy source such as electricity
- ii. Heat recovery from high-temperature gases with large amounts of contaminants such as particulates, combustibles, and condensable vapors (organic, metallic, or nonmetallic materials)
- iii. Heat recovery from ultra-low temperature sources, primarily lower than 250°F
- iv. Heat recovery from low- to medium-temperature exhaust gases or air with high moisture content to recover the latent heat of water vapor. Tremendous research has shown that some advanced technologies can be used to further increase waste heat.
- v. recovery efficiency through use of concepts such as turbo-compounding, thermoelectric generation, and thermodynamic cycles. Turbo-compounding causes increase in backpressure and pumping loss which can cause fatalities to the engine. Low efficiency coupled with the high cost of materials in thermoelectric generation renders it not applicable to such small scale.

Heat transfer from exhaust needs a heat exchanger and a working fluid for production of steam, which is expanded in the steam turbine through the bottoming process to produce mechanical rotation of the turbine shaft. This shaft is coupled to the generator shaft and results in production of power. The Exhaust Gas Recirculation (EGR) and the exhaust gas line were identified as the best sources of waste heat for recovery. In some studies, organic Rankine Cycle (ORC) with ethanol as the working fluid have been realized. The ORC maintained the pressure and temperature constant using evaporators of varying geometry and a condenser with variable bypass coolant[496].

Although significant improvement has been made on diesel engines to improve their efficiency, a considerable amount of heat is still rejected to the tune of 50% of the total energy in fuel. The organic Rankine cycle has proved to be one of the most effective solutions in waste heat recovery. The use of organic Rankine cycle for waste heat recovery for electric power generation in trucks realizes up to 10% savings in fuel used. An ORC is made of the same components as a traditional steam Rankine cycle. These are namely a pump, evaporator,

a turbine or expander and a condenser. The major difference comes from the choice of working fluid: water is replaced by an organic component[496].

6.17. Summary and Conclusion

The energy transition will require the smart energy systems whose benefits include the creation of prosumers who are both consumers and producers of power, enhanced energy security, increased uptake of renewable sources by promoting decentralization of generation and creation of intelligent energy systems capable of automatic and remote control.

Cogeneration refers to simultaneous production of heat and electricity from the same energy source while trigeneration simultaneously uses the same energy source for heating, cooling and power generation which improves energy and cycle efficiencies of thermodynamic systems. while electrical efficiency of newly installed CHP systems in the generally varies between 60% to 90% while electrical efficiency of between varies between 30–55% . Therefore, by adopting cogeneration and trigeneration, energy losses will be minimised hence less primary energy use and reduced emissions and related environmental impacts.

CHAPTER 7:

BAGASSE AND TRASH AS SUSTAINABLE ENERGY RESOURCES FOR THE TRANSITION

7. Overview

This chapter contains information published by the author in references [57, 59, 64, 296, 326, 390] which present sugarcane bagasse and cane trash as a sustainable alternative energy resource for grid-based electricity generation. Sugarcane bagasse is a by-product milling sugarcane and it is an important fuel resource for the sugar industry, while trash is often left in the field after cane harvesting. Bagasse is a fibrous, low density material and has a wide range of particle sizes with high moisture content. Sugarcane bagasse (SCB) is among the most abundant agricultural residues globally in sugar producing countries. Bagasse has traditionally been used as a fuel for production of steam and electricity needed by the sugar factories, but has other applications production of ethanol, paper and pulp manufacture, charcoal briquettes manufacture and biogas production. The need for diversification by sugar factories due to growing decentralization of generation and reducing global sugar prices due to excess sugar stock in the world market making bagasse an attractive fuel for grid-based electricity generation. This study identified the various properties and characteristic physical, chemical, and thermodynamic properties of bagasse and sugar cane trash as fuels in the sustainable energy transition. Bagasse has various pathways for exploitation as a renewable and sustainable energy resource i.e. direct combustion in boilers to produce heat for steam and power generation, anaerobic digestion to produce biogas and pyrolysis and gasification to produce syngas. Syngas and biogas can further be upgraded to produce biomethane which has significant energy and process applications as a substitute of natural gas. Bagasse has got three major components, namely pith, fiber, and rind.

7.3. Introduction

The sugarcane crop is grown globally under a wide range of climatic conditions, in the subtropical and tropical regions between 35°N in Spain to 35°S in South Africa. The crop has rain requirements of between 1,200-1,600 mm/year. If the rain is well distributed, irrigation is not necessary, otherwise the crop can also be grown under irrigation. There are many sugar

cane varieties with different characteristics, but generally the crop takes 9-24 months to mature for harvest. [81, 326].

About 115 countries globally produced over 1.8 billion tons of sugarcane in 2020 for production of sugar, paper, and alcohol for the global markets as well as electricity through cogeneration. The production of sugar cane increased from 569 million tons in 1972 to 1,859 million tons in 2021 representing an average annual rate of 2.54%. Sugar cane is grown in the tropical and subtropical regions, and is the world's largest crop by production quantity, with Brazil accounting for 40%. About 79% of global sugar production is from Sugarcane while rest is made mainly from sugar beets. In the year 2017–2018, the sugarcane industry was world's second-largest crop-production industry, which emphasis the significant socio-economic role of the sugarcane crop industry globally[621],[622],[623]. In terms of sugar production, India was the largest producer for the year 2021/2022 producing about 36.88 tons of sugar followed by Brazil at 35.35 million metric tons while the global sugar production stood at roughly 181 million metric tons in 2021/2022 period[624]. The processes in the sugar manufacture and auxiliary services for the plant need continuous and reliable energy supply which can be supplied by bagasse through appropriate cogeneration technology[625, 626]. Besides sugar as the main product in many sugar factories, bagasse contains significant energy potential as a combustion a fuel for power generation[59].

Sugarcane is a major crop in many countries globally grown commercially to produce sugar. Sugarcane is an efficient converter of the solar energy into biomass through photosynthesis with the main components of sugarcane being sucrose, and fiber. The sugarcane plant has one of the highest bioconversion efficiencies with ability to efficiently fix solar energy, to yield up to 55 tons of dry matter annually per hectare of land under cultivation. The manufacture of sugar from sugarcane has four main byproducts i.e. cane tops, bagasse, filter muds and molasses[627]. Bagasse has been used since the industrial revolution, in the production steam and electricity thus guaranteeing the energy self-sufficiency of sugar factories [45, 495, 628]. The harvested sugarcane leaves are left behind cane trash as the cane is transported to a sugar factory where it is crushed to extract juice at the mills or the diffuser in a process that leaves behind energy rich fibrous material called bagasse while the juice is taken to the process house for sugar making[57, 81, 326]. Sugarcane bagasse is a renewable feedstock used for power generation and manufacturing cellulosic ethanol in among other applications [81] . The

energy potential of bagasse produced is more than enough to meet the heat and electricity energy needs of a traditional as well as modern sugar factory, making sugar factories ideal for grid based decentralized power generation. The main challenge facing many traditional sugar factories is that the existing technology adopted is inefficiently designed maximize bagasse burning as a disposal strategy and energy supply limited energy for the factory use [45, 629].

The global price of sugar and petroleum products have shown variations since 1973, but the long term outlook shows a gradual increase fossil fuel prices and stagnation, in the price of sugar[627]. This scenario explains, to a large degree, global interest in diversification by the sugar industry which shows that optimum use of sugar production byproducts can support the sugarcane industry, since it is not possible to rely on sugar alone as the main product[326, 627]. Advances in technology and efficiency enhancement have made it possible for sugar factories to produce excess electricity for supply to the grid as an additional revenue stream [57, 628].

Bagasse is a pulpy fibrous material that remains after crushing sugarcane with feasible use as biofuel to produce ethanol. It is also used as heat and power generation, and as a feedstock for manufacture of paper and pulp and as building material [64]. Bagasse is traditionally combusted in boiler furnaces to generate steam for power production and process steam needed to support the sugar factory processes[59]. Efficient and economical use of bagasse is essential to for economic manufacture of sugar and production of excess electricity for export to generate extra revenue [630].

7.4. Bagasse Production

Generally, a ton of sugarcane milled on average produces 250–270 kg of bagasse with average moisture content of 50%, and more than 200 kg of straw. [628]. In many cases, bagasse is found in excessive supply for traditional sugar factories leading to challenges in waste disposal and storage for future use. It is for this reason the traditional sugar factories are designed to deliberately burn the sugar cane bagasse at low efficiency for disposal. The highest producing sugar cane nations are Brazil (33%), India (23%), and China (7%). Sugar cane crushing produces about 30% mass bagasse. Five million tons of bagasse burned brings about one million tons of fuel oil saved. Therefore, bagasse is an ideal renewable biomass energy source with zero net greenhouse gas emissions [34, 631].

7.5. Bagasse as an Energy Resource

Bagasse is the fibrous residue of the cane stalk left after crushing and extraction of the juice. It consists of fibers, water and relatively small quantities of soluble solids - mostly sugar[627]. Bagasse is combusted in boilers to produce thermal energy while carbon dioxide produced being absorbed in the next generation making it a carbon neutral process[57, 114, 630, 632]. Therefore, countries producing more sugarcane produce more bagasse, cane tops and trash, filter muds and molasses which have significant energy potential that can be exploited. An important characteristic of bagasse is its high moisture content of 45-50% depending on milling quality. This complicates its combustion and energy value by lowering it [57, 99]. Figure 7-1 shows the physical appearance of bagasse.



Figure 7-1: Physical appearance of bagasse

From Figure 7-1, it is noted that bagasse is a fibrous form of biomass consisting of fibers of different sizes and shape.

The main elements of bagasse include potassium and sodium which are present in biomass ash in the forms of oxides. Their presence can lead to fouling and ash deposition on the convective parts of the boiler. The presence of Alkali chlorides also contribute to slagging, fusion and sintering of ash particles which leads to solid deposits on boiler tubes and leading to increased corrosion and cost of operation and maintenance [631].

The fiber consists mainly of cellulose (27 percent), pentosans (30 percent), lignin (20 percent) and ash (3 percent). The calorific value (CV) of bagasse is given by the formula:

Net CV = 18 309 - 31.1 S - 207.3 W - 196.1 A (expressed in kJ/kg).

where,

S= soluble solids %,

W is moisture %bagasse and

A= Ash% bagasse[64, 326].

If W = 0, S = 2 and A = 3, then the net CV of bone-dry bagasse = 17 659 kJ/kg.

If W = 50, S = 2 and A =1 1/2 then the net CV of mill-run bagasse = 7 588 kJ/kg.

Bagasse is used for the generation of steam and power required to operate the sugar factory. A typical factory producing raw sugarcane require, about 35 kWh of electricity per ton of cane and 450 kg of exhaust steam. Much progress has been achieved lately and, with continuous operation of the pans, crystallizers and centrifuges and an efficient evaporation station, a modern raw sugar factory can now operate with 30 kWh and 300 kg of exhaust steam per ton of cane. Such a factory can save 50 percent of the bagasse it produces and this bagasse can be used to produce electricity for the grid or saved as raw material for the production of paper, board, furfural, etc.[81, 627].

7.6. Quantity and Energy Potential of Bagasse

Sugarcane consists of dissolved solids called brix, water, and fiber. Fiber is an important component, of sugarcane that determines the quantity of bagasse produced. Sugar can generally consists of 11 to 16% sucrose content, while bagasse levels range from 27 to 38%[633]. Bagasse yield varies widely, for example in Brazil, one ton of cane on average yields 280 kg of bagasse, but in Nepal, the average yield is 362 kg of bagasse per ton of cane milled. The average bagasse saving ration is less than 10% for a conventional sugar factory mainly because of inherent combustion inefficiencies of the traditional low pressure and temperature boilers and use of inefficient backpressure steam turbine In a typical sugar factory, every 10 tons of sugarcane milled generates about 3 tons of sugar cane bagasse. Bagasse as a fuel has sufficient energy that can be used to supply the entire energy needs of a factory for steam and power generation thus making the industry self-reliant with respect to steam and power needs and export the excess energy and earn extra revenue [634]. It also has been the principal energy resource used around the world in the sugarcane agro-industry

because of its well-known energy properties[635]. The sugar making process normally converts over 25% of the initial weight of sugarcane to bagasse. Bagasse is rich in moisture whose composition varies between 45 and 55%. In a typical Brazilian scenario 280 kg of wet bagasse produced from a tone of milled cane making it a significant byproduct of a sugar cane factory [621], [635].

Bagasse produced by a traditional factory is more than the energy requirement of the factories and often cause a disposal nightmare. For this reason, the traditional sugar mill is design to inefficiently burn off bagasse a waste disposal strategy. It is estimated that use of more efficient bagasse boilers can reduce bagasse consumption by up to 36%. Which can be used for more steam and power generation or can be used as feedstock for other processes like bioethanol production [57],[59].

7.7. Composition of Dry Bagasse

According to [636] Bagasse is a heterogeneous fibrous residue formed after juice extraction from sugar cane at the mill. Generally, milling 100 tons of sugarcane generates 30–34 tons of bagasse of which 22–24 tons is used to supply energy for sugar production with about 8–10 remaining as excess in a conventional sugar factory. According to [633] 30–32 % of the weight of the cane is generated as coproducts. Bagasse consists of 45–55 % cellulose, 20–25 % hemicellulose, and 18–24 % lignin.

According to [637] sugarcane bagasse is composed of approximately 50% cellulose, 25% hemicellulose and 25% lignin. The high cellulose content makes bagasse ideal for use as composite reinforcement material. Various research has recorded different chemical compositions for bagasse. The crystallinity in sugarcane bagasse is about 47% and most of the cellulose in bagasse is in a crystalline structure. An elemental analysis of bagasse shows that it is composed of 45.5 wt% C, 5.6 wt% H, 45.2 wt% O and about 0.3 wt% N. Additionally, the metal elemental analysis of bagasse shows that it contains 3.89 wt% Al^{3+} , 3.87 wt% Ca^{+} , 1.32 wt% Mg^{+} , 0.97 wt% Na^{+} and 27.0 wt% Si^{4+} (Jústiz-Smith *et al.* 2008). It should be noted that the presence of these metals in the fibers increases the brittleness of bagasse[637].The composition of dry bagasse is summarized in Table 7-1.

Table 7-1: Compositing of dry bagasse[638]

	Constituent	Composition %
1	Cellulose	45-55
2	Hemicellulose	20-28
3	Lignin	18-24
4	Minerals	1
5	Ash	1
6	Sugar	5
	Total	100

From Table 7-1, it is noted that dry bagasse consists of about 28% hemicellulose, 45% cellulose, 1% minerals, 20% lignin, 5% sugar, and 1% ash. The composition of bagasse is like wood, but it contains higher moisture content. This makes bagasse ideal for manufacture of paper and pulp, biofuel, filler for building materials and as a substrate for the growing of mushrooms. The fact that bagasse available is more than what is needed for the energy needs of the sugar factories makes it a candidate for value addition[638].

Sugarcane bagasse has two major types of fibers i.e. rind and the inner pith. The fibers in rind are useful because of their longer length and relatively better mechanical properties compared to fibers from inner pith which have wide applications but have inferior mechanical properties due to short lengths [290]. The stems of cane contain mainly pith (5 %), fibers (73 %), and the rind (22 %) [639, 640]. Pith and the outer rind are sources for fibers in sugar cane. Pith is lighter with a considerably lower density of about 220 kg/m³ and made up of coarse fibers and large cavities compared to rind whose density is density 550 kg/m³ [633].

7.8. Thermodynamic Properties of Bagasse

The main application of bagasse is as fuel for steam and power generation for process consumption in juice treatment, fermentation, drying and other thermal applications and can use a minimum of 50% of the bagasse generated, with the remaining bagasse or excess bagasse requiring some form of disposal or alternative application and may lead to safety and health issues like spontaneous combustion, and fermentation. It is for this reason that sugar

factories deliberately burn excess bagasse mainly through deliberate inefficient combustion at the boilers [621], [635].

The calorific value and humidity of biomass are the main determinants of the energy content of bagasse and other biomass. The average caloric value of dry bagasse is about 18 MJ/kg as compared to other fuels e.g. bituminous coal has 30.2 MJ/kg, while dry wood is 19.8 MJ/kg [641]. According to [641], the use of bagasse as a fuel can reduce carbon dioxide emissions by about 8% and meet the entire energy demand of the sugar industry.

Bagasse with 50% moisture content has a gross calorific value (GCV) of about 8.816kJ/kg to 9,600 kJ/kg while the net caloric value is about 7,600 kJ/kg. The gross calorific value of dry ash free bagasse is about 17,632 kJ/kg -19,400 kJ/kg[81, 642]. Sugar cane crop has fiber content of 10- 17% by mass which forms bagasse on milling. About 24 -30% i.e. about is about one quarter of the weight of sugar cane milled is bagasse [57, 99, 326]. The calorific value of the various bagasse constituents is shown in Table 7-2.

Table 7-2: Calorific value of different bagasse constituents [81, 642]

Item	Constituent	Calorific Value (kJ/kg)
1	Fiber	19,320
2	Sugar	16,611
3	Impurities	17,220
4	Water	0

From Table 7-2, it is noted that the main components of bagasse are water, fiber, sucrose/sugar, and impurities. However, water is the non-combustible component as the rest i.e. and noncombustible elements of bagasse fuel while fiber, sucrose/sugar, and some impurities are the combustibles.

The physical properties of bagasse from different sugar cane varieties may vary slightly but, the gross calorific value of dry bagasse is almost constant different varieties and from different countries. Table 7-3, below shows a summary of the gross calorific value of bagasse from different countries.

Table 7-3: GCV of bagasse by state/Country[81, 642]

Country	GCV of Dry Bagasse (Kj/kg)
Australia	19,076
South Africa	19,257
Hawaii	19,412
Cuba	19,702
Puerto Rica	19,295
Average	19,488

From Table 7-3, it is observed that the average (GCV) 19,488 kJ/kg of dry bagasse. However, since dry bagasse has about 6-7% moisture content, or an average of 6.5%, the gives net calorific value of NCV is about 17,850kj/kg.

7.9. Environmental Impact of Bagasse and Mitigation Measures

7.9.2. Emissions

The main pollutants from bagasse fired boilers is the particulate matter caused by the turbulent movement of flue gases from bagasse combustion and the resultant ash. Bagasse has low levels of sulfur and nitrogen compared to conventional fossil fuels hence the low sulfur dioxide (SO₂) and nitrogen oxides (NO_x) in bagasse combustion. Dirty cane influences the bagasse's ash content while neglecting combustion conditions increases emissions of unburned organics and carbon monoxide (CO), expressed as volatile organic compounds (VOCs) and total organic compounds (TOCs)[631].

Bagasse power installations mainly use wet scrubbers and mechanical collectors to control the particulate emission from boilers. The impingement and venturi scrubbers are the types of wet scrubbers primarily applied in bagasse boilers. Impingement scrubbers are installed on the gas-side and have the benefit low energy requirements and relatively low maintenance problems and incur pressure drop of 5 to 15 inches of water. For venturi scrubbers, the pressure drop is over 15 inches of water. Both scrubbers have collection efficiency of over 90 %[631]. Mechanical collectors may be installed as a single cyclone, double cyclone, or

multiple cyclone dust collector and have collection efficiency of between 20 to 60 %. The performance of the mechanical collectors may negatively impacted over time due to the abrasive nature of bagasse fly ash and the erosion if the system [631]

7.9.2.1. Bagasse Ash

The combustion of bagasse produces about 3–5% of its weight as sugarcane bagasse ash (SCBA) [621]. Leading sugar-producing nations have been generating high volumes of sugarcane bagasse ash (SCBA) as a by-product. SCBA has the potential to be used as a partial replacement for ordinary Portland cement (OPC) in concrete, from thereby, mitigating several adverse environmental effects of cement while keeping the cost of concrete low. Most of the microstructure of SCBA is composed of SiO_2 , Al_2O_3 , and Fe_2O_3 compounds, which can provide pozzolanic properties to SCBA. In this paper, literature on the enhancement of the mechanical properties of SCBA-incorporating concrete is analyzed. Corresponding process parameters of the SCBA production process and properties of SCBA are compared to identify relationships between the entities. Furthermore, methods, including sieving, post-heating, and grinding, can be used to improve pozzolanic properties of SCBA, through which the ideal SCBA material parameters for concrete can be identified. Evidence in the literature on the carbon footprint of the cement industry is utilized to discuss the possibility of reducing CO_2 emissions by using SCBA, which could pave the way to a more sustainable approach in the construction industry [621].

There can be a high variability in the ash content of sugarcane bagasse. This is largely due to variations in the practices used for harvesting the sugarcane. In some cases, the harvested crop can contain a significant proportion of soil, a trend that will lead to increased ash in the bagasse. Figure 7-2 shows the various applications of ash from bagasse fuel combustion.

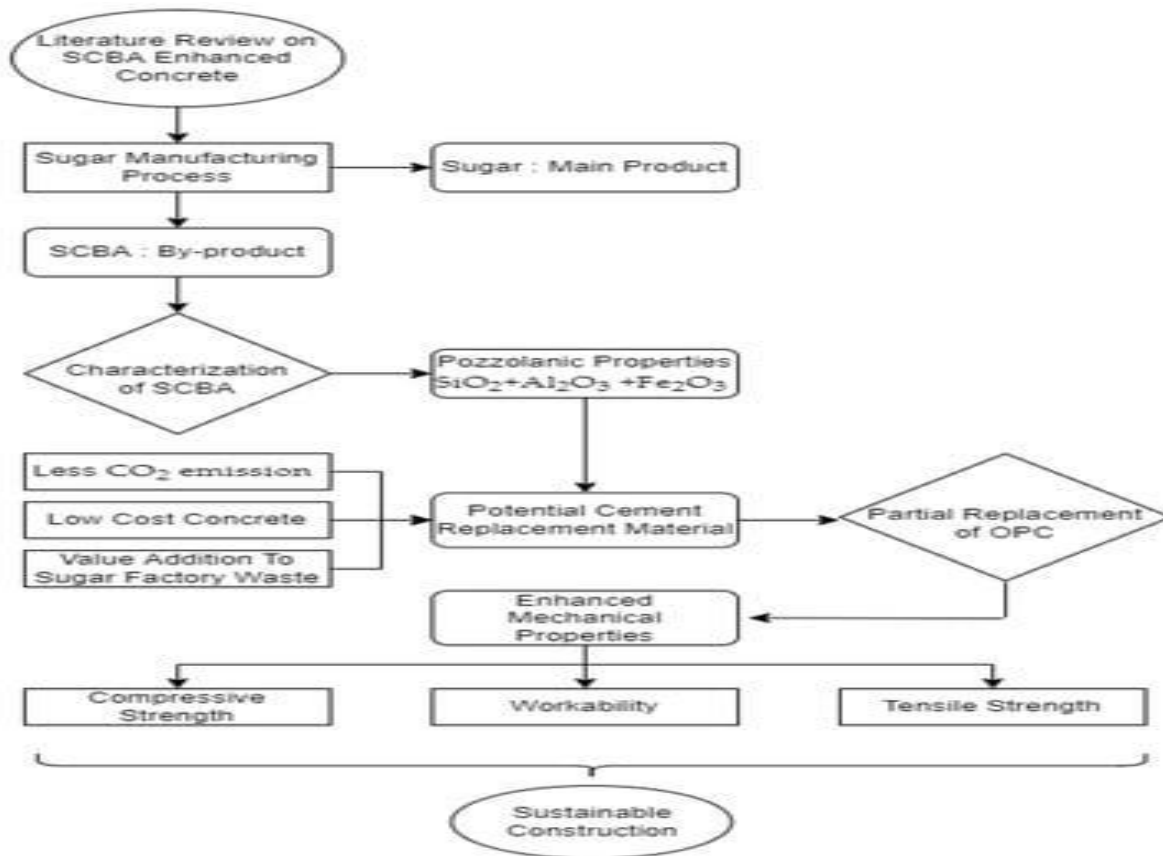


Figure 7-2: Production of ash and use in cement manufacture [621]

Figure 7-2 shows the process of ash production and feasible applications. Sugar cane ash can be used in manufacture of cement with additional value addition to the sugar industry, low-cost concrete, and lower emissions as benefits.

7.10. Sugar Cane Trash as Fuel for Cogeneration

Sugarcane has emerged as an interesting complementary fuel for the sugar cane factories. Trash is the residue usually left in the sugarcane field in quantities representing about 125 kg trash/ton of cane harvested.

7.10.2. Physical and Chemical Properties of Sugar Cane Trash

Sugarcane consists of clean stalk (72%), the cane tops are 8% and leaves 20% while the amount of trash that remain in the field after harvesting depends on the harvesting method, cane variety, and moisture content (MC) of trash. The moisture content for tops and leaves is about 65% and 15% respectively on weight basis. Since leaves have about three times more silica than tops, the high silica content (2.76%), makes the fodder not recommended for the

livestock. The lignin content in tops is about 60% higher than leaves. The high lignin and silica restricts the application of sugarcane trash (ST) for fuel purpose and use as livestock fodder[643]. The sugarcane tops and dry leaves have differences in nutrients content and moisture content. About 80 % of N, P and K is derived from the sugarcane tops hence more nutritive and valuable to the soil leading to use of less mineral fertilizers for sugarcane cultivation. Additionally, the tops have about seven times more moisture than dry leaves and have higher levels of extractives organic compounds of low molecular weight. It is predicted in studies that dry leaves are more viable for production of second generation ethanol production compared to tops due to better results of yield in the pretreatment steps for dry leaves although glucose yields obtained in the enzymatic hydrolysis step were similar [643],[644]

The chemical composition of sugarcane trash in terms of average per cent ash, lignin, cellulose, and hemicellulose is about 7.17 ± 1.65 , 20.18 ± 5.75 , 44.55 ± 4.70 and 27.44 ± 2.54 , respectively. The carbohydrate and silica content in sugarcane trash is about 57.5% and 6.96%, respectively. This shows that trash has potential applications in biochemical conversions like anaerobic digestion for biogas production, biofuel processing and ethanol production[466]. Therefore, trash has significant potential for power generation, production of 2nd generation ethanol and production of other biochemical products [644].

7.10.3. Energy Potential of Trash

Possible pathways in the use of trash for energy purpose conversion to syngas mixed with the bagasse or co-firing with natural gas at the gas turbines or can be used in an afterburner to supply extra/ additional energy directly to the heat recovery steam generator HRSG[645]. It is however operationally easier to transport straw along with sugarcane in the same truck which increases handling costs [466].

Sugar cane trash has got same energy as bagasse, but it is wasted during open burning at the farms. It is estimated that trash contains about one-third of total energy contained in sugarcane. Sugar factories and sugar producing nations can realize some sustainable and socioeconomic development by harnessing energy in sugarcane trash through creation of extra employment opportunities and conservation of the environment and further contribute to profitability and sustainability of sugar factories. The main limitation is the technological and

economic challenges to utilize in commercial exploitation of sugar cane trash. for steam and power production. Specific constraints include lack of technological awareness, lack of incentives, poor purchasing power of the farmer and lack of market for the trash or energy [643],[646].

Besides bagasse as a boiler fuel, trash is a significant material that can be used as boiler fuel. Trash is the residue left in the field after sugarcane is harvested, comprising mainly of leaves and the tops of the plant; cane portions with low or insufficient sucrose content hence not worthy for juice extraction in milling[647]. On average basis, every ton of sugar cane harvested yields about has, 140 kg of trash. However, this only applies in the case of mechanically cane harvesting which involves the trash being blown back onto the field during harvesting as opposed to manual harvesting where the crop is burnt prior to harvesting by workers who chop the stems. This burns leaves and only leaves the stems and roots as trash. Manual harvesting is a common practice in developing countries including Brazil which had set a targeted 2020 for all harvesting to be mechanical [621], [635],[81].

Dry sugarcane trash contains about 28% of the total energy content in the sugarcane crop. In the study by[647], it was noted that in India alone, if all the cane trash is utilized for energy purpose, the national energy deficit can be cut by 50% and the sugar industry can generate additional 110% power for export.. Sugarcane trash contains more silica and alkali making it undesirable as a boiler fuel directly[81],[647]. Therefore, trash processed with the cane supply should be thoroughly washed at mills to reduce the alkali and silica content of resultant bagasse for cases where trash is harvested together with sugar cane and delivered to the factory [647].

7.11. Bagasse To Energy Conversion Pathways

Bagasse like other biomass energy resources can be extracted by direct combustion or conversion into gaseous fuels like biogas and syngas and then combustion of the intermediate energy carriers to release energy. Anaerobic digestion of biomass involves bio-digestion of biomass with high moisture content in oxygen deficient to produce biogas. Gasification on the other hand is ideal for conversion of particularly for low-moisture biomass into syngas in as environment with limited amount of air at high temperatures [463].

Biomass energy resources can be extracted by direct combustion or conversion into gaseous fuels like biogas and syngas and direct combustion of the intermediate energy carriers to release energy, anaerobic digestion of biomass through bio-digestion of biomass with high moisture content in oxygen deficient and gasification by conversion of generally low-moisture biomass into syngas in limited amount of air at high temperatures [310].

The main challenge of bagasse as an energy resource is the high moisture content and low calorific value, high oxygen content, the hygroscopic nature of bagasse, and heterogeneous properties which causes challenges in handling, storage, transportation, and combustion or conversion [36]. The various conversion pathways are discussed below.

7.11.2.Direct Bagasse Combustion

In this process, solid state is burned in an excess of air in boiler furnaces to produce heat which is used for steam generation. The steam generated is used to run a Rankine cycle steam turbines for power generation as well as prime movers for sugar factory plant and equipment like for mill drives as well as cane knife turbines [45, 551]. Efficient combustion may need extra drying process to reduce to an optimum level except for anaerobic digestion [310].

7.11.3.Bagasse Gasification

Biomass gasification is a thermochemical conversion process done in limited supply of oxygen to produce a gaseous mixture called syngas which mainly consists of hydrogen and carbon monoxide[310]. For gasification, the carbon conversion rate is the key measure of the efficiency of gasification process. A circulating fluidized bed gasifier has a maximum carbon conversion rate of 98–99%[310]. Gasification is a thermochemical conversion of a carbon-rich biomass to useful combustible gas mixtures e.g. carbon monoxide, hydrogen, and methane by reacting biomass with oxygen in air steam, and carbon dioxide at temperatures higher than ($>600\text{ }^{\circ}\text{C}$)[648].The maximum carbon conversion of a circulating fluidized bed gasifier can be as high as 98–99% [310, 649].

Gasification systems can supply clean products for use as fuel or synthesis gases in an environmentally friendly processes[649]. Unlike anaerobic digestion, gasification and direct combustion perform better with low moisture content of biomass [310]. The reaction in gasification normally takes place at high temperatures, usually above 1000°C in limited supply of oxygen and/or steam. The product of gasification is syngas or producer gas whose heating

value is 4-6 MJ/kg. Use of syngas is potentially more efficient than direct combustion of the original like bagasse. Bagasse gasification generates some CO₂ but it is the CO₂ consumed during the growth of the crop rendering the process a carbon neutral process [650].

For sugarcane bagasse, gasification starts with pyrolysis, then gasification of the char formed. The properties of syngas produced depends strongly on the heating rate and temperature of the sample. Pyrolysis involves a series of hydrocarbons breakdown, fragmentation, isomerization and repolymerization. For high heating rates and high reactor temperatures, the gasification and steam reforming reactions happen parallel with some of the pyrolysis reactions [651]. Some end use technologies like turbines or synthesis gas systems demand high quality gases. Although boilers too have fuel quality requirements, the quality is not as stringent as the gas turbines. Gas from biomass gasifiers have some impurities in form of particulates, tars, and other constituents that may go beyond minimum recommended limits. Therefore, gas cleaning and conditioning becomes a necessary investment [649].

7.11.4. Anaerobic Digestion

This is biological conversion process organic matter is digested in the absence of oxygen to produce biogas. Biogas is a mixture of gases with methane and carbon dioxide as the main components. Perennial crops e.g. miscanthus and willow yield lower specific methane yields than annual crops like corn e.g. 0.20 m³ of CH₄ compared to 0.36 m³ CH₄ per kg volatile solid (VS) in anaerobic digestion, mainly because of the lignocellulosic structure[390].

The anaerobic biodegradability and methane yield from perennial crops can be enhanced by application of suitable pre-treatment e.g. wet oxidation which is a thermal pre-treatment method done under high pressure and temperature of between 185 and 220 °C, and oxygen pressure of between 0–12 bar for a period of 15 min. The pretreatment increases methane yield for perennial crops to about 0.36 m³ CH₄ (or. 0.65 m³ biogas) per kg of VS, considering that about 5% of the organic matter is in the process. Not all methane potential can be extracted at once in anaerobic digestion, because storing digestate uncovered in tanks, leads to methane loss to the atmosphere from spontaneous degradation [649].

7.11.5. Fermentation

Sugarcane bagasse (SCB) is an attractive feedstock for the large-scale biological production of bioethanol due to its abundance. It is however limited by its high degree of complexity due to

mixed composition of extremely inhomogeneous fibres which makes ethanol production from bagasse a complex process involving size reduction; pretreatment; enzymatic hydrolysis for sugar extraction; liquid-solid separation of pentose rich (hemicellulose) hydrolysates; purification/detoxification of hemicellulose sugars; fermentation of hexose and pentose hydrolysates separately or mixed; distillation to separate bioethanol; and utilization of residual solids which are rich in lignin often as a boiler or furnace fuel [652, 653].

7.12. Comparison of Conversion Technologies

None of the three feasible bagasse conversion technologies i.e., direct combustion, gasification, and anaerobic digestion is 100% carbon conversion efficient. It is for this reason that there is some amount of residue as ash or the digestate, whose magnitude depends on the carbon conversion efficiency of the process. Biochar carbon is the residue carbon contained in biomass ash from direct combustion especially in gasification. Biochar is the charred organic materials produced from incomplete biomass combustion. Sequestration of carbon through production and deposition of biochar has ability to fix 85% of the carbon in the char which is considerably greater than that associated with incorporation of crop residues into the agricultural soil. biochar is highly aromatic structure making it more resistant to microbial degradation than the un-charred biomass[390]. Application of the digestate from anaerobic digestion to the field with residue carbon results in carbon sequestration at a rate of about 12% over 100-year period if arable land is available for use. However, this carbon sequestration rate is lower than that of biochar, hence anaerobic digestion even with wet oxidation pre-treatment cannot favor the formation of biochar which takes place at higher temperature of about 500 °C [310, 649].

For over the last two decades, sugar factories prefer burning bagasse spreader stokers. Bagasse fuel enters the furnace through a fuel chute. Then it is spread across the furnace by means of charge air allowing part of the fuel to burn in suspension. Heat generated will heat water in the tubes or water walls to generate steam [631].

7.13. Bagasse Cogeneration Systems

In the 1970s and 1980s, sugar factories were designed to inefficiently consume all the bagasse in production of steam and electricity for internal use. The systems were so inefficient that some factories needed additional fuel from elsewhere to meet their energy needs[81, 654]. In

the 1990s and early 2000s, the sugarcane industry faced an open market perspective, and embraced the need to reduce operating and production costs with emergence of opportunities for economical use of the by-products i.e. bagasse, molasses, due to increased decentralization of power generation and the quest for renewable energy sources and increased demand for bioethanol from bagasse and molasses. These developments led to a search for more advanced cogeneration systems, using higher steam parameters, while in future, even more advanced systems like biomass integrated gasification combined cycles may be adopted by the sugar mills [632, 655]. These cogeneration systems can attain 35–40% efficiency in power generation. Supercritical steam cycles can also realize such efficiency values, making them attractive alternative to gasification-based systems [654].

The existing modern, high pressure, high efficiency, steam turbine cogeneration plants generate 115–120 kWh/tc, while BIG-GT and BIG-STIG are potentially capable of generating up to 270–275 kWh/tc. Cogeneration plants using backpressure and condensing steam turbines perform with energy (First Law) and exergetic (Second Law) efficiency of approximately 60–70 % and 22–25%, respectively. The steam consumption in sugar mills at present varies from 480–550 kg/tc, while electricity consumption ranges between 16–22 kWh/tc (32–40 kWh/tc for electrified mills). These performance indices will help plant designers and engineers in improving their choice of system configuration and developing alternative schemes. Biomass-integrated gasifier/gas turbine cogeneration (BIG-GT) and biomass gasifier combined with steam injected gas turbine cogeneration (BIG-STIG) are considered as potentially promising future technologies. [656].

There are different options for use by sugar factories to simultaneously generate electricity, sugar and ethanol [655]. The different cogeneration options are.

7.13.2. Conventional Backpressure Steam Systems (BPST)

The back-pressure steam turbine (BPST) system utilizes a back-pressure turbine with exhaust pressure above atmospheric pressure normally 1.5 to 2.5 bar for process use. These are the most common configuration in many sugar factories. The back pressure system can still generate excess electricity through process modernization to reduce steam consumption as well as steam and power generation efficiency improvement. [657].

7.13.3. Condensing-Extraction Steam Systems (CEST)

The condensing steam turbine plant performs with typical energy and exergy efficiency of 0.682 and 0.260, respectively. In a bagasse power plant, the boiler is the least efficient component and turbine is the most efficient component of the plant [658].

The condensing extraction steam turbine system is applied as an option in which a condensing-extraction turbine is used to supply low pressure steam extracted from the expansion for process application while the excess is exhausted to the condenser [59, 657]. Both BPST and CEST can use different steam generation temperatures and pressures e.g. 42 bar/400 °C, 42 bar/ 450 °C, 67 bar/480 °C, 67 bar/515 C, 80 bar/520 °C, 100 bar/520 °C and 120 bar/540 °C [657].

7.13.4. Supercritical Steam Systems

The supercritical steam system is an improvement of the condensing extraction steam system. The system uses very high steam parameters and regenerative heat exchangers for preheating boiler feed water which effectively improves the cycle efficiency. This system can also apply a gas turbine for power generation thus a biomass gasification-based system is a possible option. Bagasse and cane trash is dried and sent to a gasifier, to produce producer gas which is used as a fuel in the gas turbine system while turbine exhaust gases are passed through a Heat Recovery Steam Generator (HRSG) to generate steam for use in a condensing-extraction turbine for extra power generation [81, 654].

7.13.5. Biomass Integrated Gasification Combined Cycles (BIGCC)

There are two main configurations for BIGCC technology i.e. low pressure air-blown and high-pressure air-blown [654, 657]. The BIGCC is made up of four major subsystems, namely, fuel system for handling and feeding fuel to the BIGCC system, the gasifier, the gas clean-up unit (GCU), and combined cycle system. The gas turbine system and steam turbine system are integrated together [654, 655].

7.13.5.1. Biomass-Based Integrated Gasification Combined Cycle (BIGCC) Technology

Biomass gasification is used in many large powers using biomass. However, its application in sugar industries because of its high potential has been considered only recently. Biomass gasification is defined as the process of incomplete combustion or partial oxidation of biomass

that further results in the production of combustible gases comprising of carbon monoxide and hydrogen. Thus the main aim of biomass gasification is to not only increase the heating value of product gas but also to maximize the conversion of solid fuel carbon[659]. There are two main configurations for BIGCC technology. They are low pressure air-blown and high-pressure air-blown [654, 657]. The BIGCC is made up of four major subsystems, namely, fuel system for handling and feeding fuel to the BIGCC system, the gasifier, the gas clean-up unit (GCU), and combined cycle system. The gas turbine system and steam turbine system are integrated together [654, 655].

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BIG-CC system offers both better electricity generation and high cost as compared to conventional systems. In BIG-CC system, the process is divided into five parts namely: biomass gasifier, gas cleaner, gas turbine cycle, steam turbine cycle and a heat recovery steam generator (HRSG). Figure 7-3 shows the main features of the BIGCC technology.

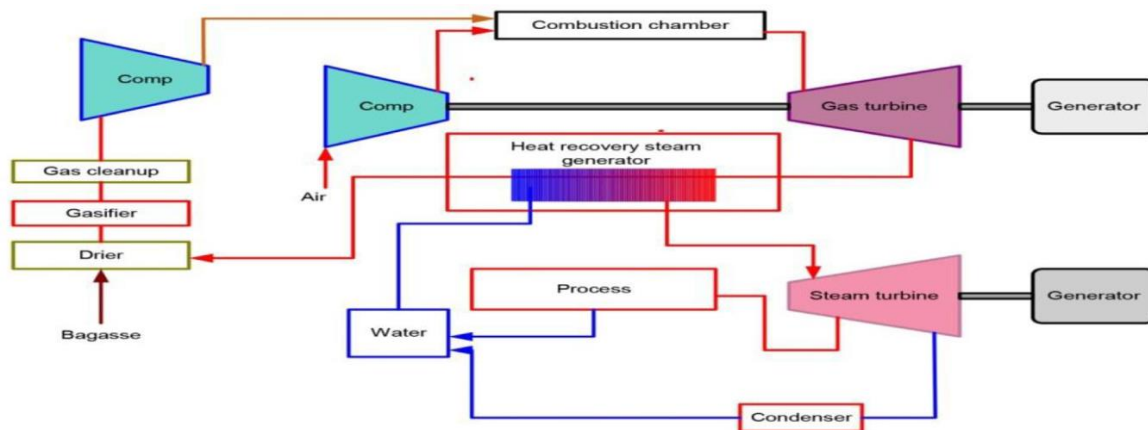


Figure 7-3: BIGG [659]

Figure 7-3 shows the biomass integrated gasifier power plants which combine the gas turbine and Rankine cycle turbines for power generation. The model comprises of two main parts: combustion and gasification. The wet bagasse is first dried and fed into the gasifier. To run an electric generator, product gas obtained from the gasifier after the process of filtration and

cleaning is fed into the gas turbine cycle. In this, compressor plays an important role. It is connected to combustor. This combustor aids in accommodation of large product gas for its fuel. The exhaust gases from gas turbines are used to serve two purposes- generate steam in heat recovery steam generator (HRSG) as well as aids in running a bottom steam Rankine cycle [18]. This is done to get additional electricity. The exhaust flue gases released from the HRSG are then used in a bagasse dryer to extract waste heat. The moisture content of bagasse is further reduced to < 20% for higher potential [659]. This depends on the type of gasifier used.

7.13.6.Multi-Fuel Bagasse-Cogeneration

Different substances or fuels can be used as the fuel for Combined Heat and Power (CHP), such as natural gas, coal, biomass waste, diesel, etc. The overall efficiency is as high as 80–90% in CHP compared to conventional plants whose power plant electricity efficiency is approximately 35–40%. The high total efficiency in CHP means that the CO₂ emissions per heat and electricity unit produced are significantly reduced [660]

In the study by [660] an energy-focused environmental accounting method based on the embodied solar energy (emergy) principle was used for evaluating biomass and coal-based combined heat and power (CHP) cogeneration processes. The emergy method expresses all the resources needed (fuel, investment, labor etc.) as solar energy equivalents. The method looks at sustainability from the point of view of the biosphere. In fact, emergy aims to be a 'memory' of how much work the biosphere has done to provide a product [390].

Biomass and coal-based CHP alternatives were compared with independent production of heat & power. It was found that biomass-based cogeneration is 3.3 times more emergy-efficient than coal-based independent production, i.e., the biosphere needed to work 77% less for biomass CHP produced heat & power compared to that produced independently from coal. Cogeneration from the same fuel was in all cases 0.3 times more emergy-efficient than independent production. In general heat and power production from biomass is 2.3 times more emergy-efficient than that from coal in a similar process. The emergy sustainability index shows a similar trend, e.g., the sustainability index of a biomass CHP plant is 15 times higher than that of a coal CHP plant. The fuel, its transport, and the oxygen in air used for burning

account for over 80% of the energy in biomass CHP, whereas in a coal-based process the share is over 90%. The share of capital is quite small in terms of total energy.

7.13.7. Cogeneration Potential of Sugar Factories

Cogeneration in sugar factories increases the total energy efficiency of the sugar factory increases to about 50%[34, 115]. The traditional factories generate just enough electricity and steam for factory internal use while high efficiency cogeneration sugar mills have boilers with high thermal efficiency, more efficient condensing extraction steam turbines or other efficient turbines to produce excess electricity and have modernized process equipment and drive systems that consume less steam and electricity to maximize the power production and export[81, 326, 661]. The energy potential of bagasse is determined mainly by the moisture content and the energy generation technology applied in power and steam generation. The electric power output is fundamentally dependent on market rules and incentives available like feed in tariffs and other drivers of production efficiency [326, 661].

7.13.8. Sugar Factory Electricity and Steam Demand

The thermodynamic performance of a bagasse cogeneration facility can be expressed in the form of energy utilization factor, heat-to-electricity ratio, fuel saving ratio exergetic efficiency, and electricity produced per ton of cane[81, 662]. Cogeneration plants using high pressure, Rankine cycle steam turbine generally produce 115–120 kWh/tc, while BIG-GT and BIG-STIG very high generation potential of 270–275 kWh/tc. Cogeneration with the backpressure and condensing steam turbines have energy and exergetic efficiencies of about 22–25%, and 60–70% respectively. Other important parameters for the sugar factory and bagasse cogeneration power plant are the steam consumption which varies between 480–550 kg/tc milled. The electricity demand of a sugar factory varies between 16–22 kWh/tc for mill turbine driven mills and 32–40 kWh/tc for electrified mill drives [59, 326].

Sugar production is an energy intensive undertaking which requires energy mainly in the form of heat/steam and electricity. In the conventional or traditional factory, a back-pressure turbine supplies electricity and steam from its exhaust for process use. The modern sugar mills generally use the condensing extraction (CEST) which is more efficient to generate electricity in excess for internal use and sale to the grid while extracted/bled off steam is used for process thermal applications. The main sugar factory energy consuming equipment are the cane

knives, cane carrier elevators, the gantry cranes at cane yards, the mill drives, conveyers, pumps, evaporators, pans, centrifuges, and mills have either electric drives or steam turbine drives[494, 642]. The mills and cane knives are driven by either steam turbines or electric motors although electric motors are considered to be more energy efficient [64].

7.13.9. Electricity Potential of Sugar Factories

The conventional sugar mills with no power export generally produce 10-20 kWh electrical energy/tc and consume 480-550 kg steam/tc, while modern mills applying efficient conversion systems produce electrical energy in the range of 115-120 kWh/tc. Application of steam saving measures in the sugar factory releases steam from process and milling application to production of extra power. From various studies on bagasse cogeneration, it was established that reducing steam consumption from 500 by 30% to 350 kg/tc increases power generation by 24% while partial use of cane trash can increase excess power generation by one or two folds[57, 81, 311]. The efficiency of conventional cogeneration systems using back pressure turbines is about 25% at steam pressures of 20-30 bars. For systems using pressure of 45-66 bars, the electricity potential is about 100 kWh per ton of milled. For high pressure boilers of average of 82 bars, the generation capacity is about 110-130 kWh per ton of cane crushed based on experience from Reunion, Mauritius, India, and Brazil [45, 59, 296, 390, 551].

7.13.10. Sugar Factory Cogeneration Configuration

There are three basic bagasse cogeneration configurations applied, namely, intermittent generation in which the power generation is based on sugar production needs, continuous cogeneration power plants that are designed to operate continuously during the sugarcane crop season with bagasse as main fuel and the firm power plants which operate throughout the year except for planned maintenance. Firm power normally operates for 300 days and are stopped for 65 to 66 for routine maintenance [64]. The characteristics of the three types of bagasse cogeneration power plants are shown in Table 7-4

Table 7-4: Comparison of the three cogeneration setups that can be adopted by sugar mills.

Parameter	Intermittent Generation	Continuous Generation	Firm power Generation

1	Power generation capacity (kWh/ton)	10	60	110-130
2	Cane milling rate	10 TCH or 240 TCD	150 TCH or 3,600 TCD	230 TCH or 5600 TCD
3	Load factor and availability	Intermittence allowed	Continuous at 90% load factor	Continuous at 90% load factor, 300 milling days or 7200 hours a year and 65-66 days for maintenance.
4	Ratio of Steam to bagasse	1.8:2.2	2.5	2.5
5	Steam pressure (bars)	25 to 30	30-45	82
6	Type of turbine used	Back pressure	Condensing	Condensing type
7	Boiler capacity (tons/hr)	40	120	140-150
8	Steam consumption	500-600 kg/ton of cane crushed	400 kg/ton of cane milled	400 kg/ton of cane milled
9	Electricity consumption	25 kWh/ton of cane crushed	30% internal consumption	Not more than 30% internal consumption
10	Turbine capacity	0.5-3 MWe	At least 15 MW	At least 30 MW

From Table 7-4, it is noted that firm power plants have the highest generation capacity and use boilers with highest steam pressure of 82 operate at high load factors of 90% followed by the continuous power plants which also operate at a load factor of about 90% bars and use boilers with medium pressure range of 30 to 45 bars. The intermittent power plants usually use low pressure boilers of pressure 25 to 30 bars which are associated with the traditional sugar factory conditions[390].

The internal electricity consumption is limited to 30% for the continuous and firm power plants while the intermittent power plants generally consume 25 kWh/ton of cane milled. The steam to bagasse ratio is 2.5 for the continuous and firm power plants hence more efficient than the intermittent whose ratio is 1.8:2.2. on average basis. Another indicator of steam efficiency is the steam consumption which is 400 kg/ton of cane for continuous and firm power plants and 500-600 kg/ton for the intermittent mills. The average turbine capacity for an intermittent power plant is 0.5 to 3 MWe for intermittent power plants, 15 MWe for

continuous and 30 MWe for the firm power plants. However, we have several cases of capacities beyond the stipulated range[45, 81, 551].

7.13.11. Investment Costs for Bagasse Cogeneration

The investment cost for bagasse cogeneration power plants depends on the net export capacity and technology adopted. Low pressure plants cost about \$1.4 million/MW; mid-range pressure systems cost about \$1.8 million/MW while the high pressure at the top end cost about to \$3.1 million/MW. These costs compare favorable against heavy fuel plants which cost about \$1.1 million/MW, geothermal at \$2.25 million/MW and \$2.5 million/MW for hydroelectric power plants. The advantage of bagasse power plants over the thermal power plants is that they do not have a fuel cost assuming bagasse is waste product or byproduct of sugar production process but the thermal power plants have significant fuel costs that are passed directly to consumers in addition to the electricity or energy costs [663].

7.13.12. Investment Options for Bagasse Cogeneration

Experience from past bagasse cogeneration projects around the world based on design specifications for a 5000TCD (tons per day sugar factory) in terms of bagasse consumption, generation capacity, investment capital and actual electricity generation for 45, 60 and 82 bars boiler steam configurations have parameters specified inTable 7-5.

Table 7-5: Investment guideline parameters for bagasse cogeneration projects[81]

Component	Possible plant options		
Boiler pressure (bar)	45	60	82
Recommended plant capacity (tons of cane per day)	5000	5000	5000
Boiler capacity (tons of steam per hour)	140	140	140
Bagasse feed rate (tons per hour)	58	62	70
Turbine capacity (MW)	25	30	50
Daily power generation, gross (MWh)	420	550	820
Equivalent capacity (MW)	18	24	40

Daily export power, net (MWh)	260	330	550
Equivalent export capacity (MW)	12.5	14	24
Total capital investment (\$ million)	18	25	75
Estimated local component (\$ million)	4	5	12
Estimated annual revenue from electricity (\$ million)	4	5	8.3
Simple payback period (years)	4.5	5	8.8

From Table 7-5 it is noted that, based on factory size and choice of technology, there are three types of boilers that can be selected for generation of steam based on a 5,000 TCD sugar factory. The steam pressure ranges from 45 to 82 bars or closer denominations. The annual electricity revenue is between USD4 and USD 8.3 million dollars and payback period ranges between 4.5 years and 8 .8 years based on experience from similar projects.

7.14. Results and Discussion

The boilers in traditional sugar mills generally operate at steam temperature of 300 °C and pressure of 21 bar for use in generation of process steam and electricity using backpressure turbines, with backpressure steam pressure of 1 to 2.5 bar for factory thermal applications in processes while the condensate of good quality is fed back to boiler[654]. Today, modern sugar factories use boilers with higher parameters of 40 –120 bar, and produce excess electricity for export by adopting condensing-extraction steam turbines [655], more possible future generation by adopting more efficient configurations like Biomass Integrated Gasification Combined Cycles (BIGCC), Supercritical Steam Cycles (SuSC) and other advanced gasification based systems. [654, 655].

A high ratio of cane crushed (TC)/TS (Sugar made) implies that juice extraction and sugar recovery in processes is inefficient as indicated by high bagasse pol (percentage of dissolved solids in sugar) which also causes undesirable effects to boiler combustion like formation of clinkers on boiler furnace grates during combustion of bagasse which inhibits boiler performance and efficiency by restricting flow of under-grate combustion air. High bagasse moisture content also negatively affects the combustion and steam rate by reducing the heating value of bagasse fuel. Good milling practice produces bagasse with moisture content of 45 to

50% [81],[646]. Drying bagasse is an option that can improve bagasse properties as a fuel, but economic sustainability needs further investigation under prevailing circumstances. Dry bagasse has got average universal gross calorific value (GCV) of about 19,488 kJ/kg of dry bagasse. Since dry bagasse has 6-7% moisture content, a working average of 6.5% moisture content gives net calorific value of N.C.V = 17,850kJ/kg [390].

Grid electricity from sugar cane bagasse cogeneration power plants can be applied to complement polluting and expensive fossil fuels electricity and variable sources like hydroelectric power, wind and solar while at the same time provide additional revenue streams from sugar factories. Electric power from bagasse is cleaner compared to both fossil fuels and nuclear power. Since most farmer payment regimes in most countries involves farmers being paid for the cane supplied based on sugar content, disregarding the significant energy value of the fiber which produces bagasse fuel, commercialization of electricity and other products from bagasse can generate extra revenue where the sugar cane farmer is paid for both sucrose and fiber in the cane which will increase the economic value of the sugarcane crop and sugar factories as well [34, 388, 391, 664].

Bagasse cogeneration is of immense economic value since most sugar producing countries are less developed with high levels of unemployment and low access to grid electricity. Bagasse cogeneration if successfully adopted will accelerate social and economic development for the sugar cane producing nations. Agricultural activities account for about 45% of the Sub-Saharan Africa economy. The Agro-industries need various forms of energy for production and operations, and the employees where over 313 MW of installed generation capacity is installed in five sub-Saharan countries of Kenya, Malawi, Uganda, Tanzania and Ethiopia power capacity in agro-industries with over 270 MW coming from bagasse cogeneration [322, 326, 665].

There are many benefits that come with investment in export cogeneration by sugar factories as a diversification strategy. They include revenue diversification, stabilization of the sugar industry, job creation and extra revenue and stable revenue for sugar cane farmers[494]. Cogeneration experience from countries like India, Réunion, Mauritius, Brazil and Cuba have has proved that the sugar industry can supply significant electricity to the grid which helps in

mitigating the greenhouse emissions and help countries realize their emissions and climate targets [621, 643].

7.15. Conclusion

The existing modern, high pressure, high efficiency, steam turbine cogeneration plants generate 115–120 kWh/tc, while BIG-GT and BIG-STIG are potentially capable of generating up to 270–275 kWh/tc. Cogeneration plants using backpressure and condensing steam turbines perform with energy (First Law) and exergetic (Second Law) efficiency of approximately 60–70 % and 22–25%, respectively. The steam consumption in sugar mills at present varies from 480–550 kg/tc, while electricity consumption ranges between 16–22 kWh/tc (32–40 kWh/tc for electrified mills). These performance indices will help plant designers and engineers in improving their choice of system configuration and developing alternative schemes. About 140 kg of trash is produced for every tone of cane milled [390].

Bagasse is the most abundant lignocellulose material in tropical countries among many agricultural crop residues found in over 100 countries globally. Bagasse is about 25-38% of the weight of cane milled and forms a byproduct of sugarcane milling process in the manufacture of sugar or ethanol by sugar factories. Bagasse consists of a wide range of particle sizes and contains high moisture content. Bagasse having moisture content of 50% has a gross calorific value (GCV) of about 8,816 kJ/kg to 9,600 kJ/kg while the net caloric value is about 7,600 kJ/kg. The gross calorific value of dry ash free bagasse is about 17,632 kJ/kg -19,400 kJ/kg. [390].

Bagasse contains three main components, namely, pith, fiber, and rind existing in varying proportions. Bagasse physical properties vary considerably in size and shape of the three components. Bagasse can further be divided into two major parts, namely fibrous outer part and the underlying pith. Pith consists of white, soft, smooth parenchymatous hygroscopic tissue made up of sugars, cellulose. Since the composition of bagasse is like wood but has higher moisture content makes it ideal for manufacture of paper and pulp, biofuel, filler for building materials and as a substrate for the growing of mushrooms, which are competing alternatives to energy application of bagasse. Bagasse has various pathways for exploitation as an energy resource i.e. direct combustion in boilers to produce heat for steam and power generation, anaerobic digestion to produce biogas and pyrolysis and gasification to produce syngas.

Syngas and biogas can further be upgraded to produce biomethane which has significant energy and process applications as a substitute of natural gas [390].

7.16. Recommendations

The over 115 countries that are classified as sugar producing have significant energy potential contained in close to 600 million metric tons of bagasse and over 300 million metric tons of sugar cane trash than can be used as an energy resource using the various energy conversion options i.e. direct combustion, anaerobic digestion, gasification, and fermentation. This requires a facilitating policy and legal environment, technology and facilitating energy infrastructure.

CHAPTER 8:

FEASIBILITY OF GRID BASED BAGASSE POWER GENERATION WITH CASE STUDIES

8. Overview

This chapter examines the feasibility of bagasse cogeneration by traditional and modern sugar factories and contains work published in papers [45, 57, 59, 296, 390, 551, 666]. Different cogeneration options are presented for use of bagasse in the energy transition. The study recommends various policy initiatives to promote the use of bagasse and cane trash as a fuel particularly in heat and power generation. Proposed measures include attractive feed in tariffs for cogenerated heat and power, tax incentives and measures to encourage investment, and a flexible power purchase agreement that recognizes the unique challenges facing the sugarcane manufacturing like unsteady supply of cane and hence inconsistent milling and fuel supply.

8.1. Introduction

Sugar is an important commodity for human consumption, and is additionally a vital commodity for socio-economic development making sugar cane a very important cash crop for many countries[667]. However, sugar cane products are quite vulnerable in the international market and their prices are quite volatile. [667, 668]. The ever-growing demand for energy and environmental concerns due to fossil fuel related greenhouse gas emissions and concerns over the global temperature rise have led to a shift to renewable energy resources. Biomass is an important option being a renewable energy and carbon neutral energy source [311, 669]. Agriculture is an important economic activity with different products adding value to the economies as raw materials for industrial processing or final consumer goods. Sugar cane is an example of a commercial crop used as a raw material for industrial production of sugar and byproducts with significant value addition potential like bagasse and molasses[664]. The sugar factory has become a multipurpose factory simultaneously producing food, energy, and biofuels [635]. As a transition product in the energy and economic transition, Sugarcane is it is used in production of sugar and many other by-products in more than 100 countries [326, 493].

A modern sugar cane industry is diversified and highly integrated producing a wide range of products like sugar, molasses, ethanol, electric power, pulp and paper, charcoal briquettes, biogas etc. remain sustainable and competitive in the market [81, 670]. Bagasse is an energy rich byproduct of a sugarcane factory having significant economic and technical potential for grid power generation[493]. Bagasse based cogeneration has proved to be a reliable source of grid electricity in countries that have modernized their sugar factories to increase energy efficiency[45, 551]. As evidence from countries with successful bagasse cogeneration like Mauritius, Brazil and India, development of export based bagasse cogeneration as a reliable source of grid electricity involves many stakeholders and investment in energy efficient technology and capital in a facilitating legal and policy environment [664, 671]. Several countries like Mauritius, India and Brazil have the sugar industry connected to the public power grid which earns the industry extra revenue in exchange for clean electricity[81]. India has over 500 sugar factories with bagasse based power generation of over 3,221 MW [670, 672], while the untapped potential remains more than 5,000 MW[673]. In Brazil, the sugarcane mills are the fourth leading sources of electricity supply to the Brazil's grid electricity mix, even though it is just 15% of the industrial capacity of the sugar industry with estimates showing that sugarcane residues, bioelectricity can supply 148,000 GWhrs to the grid[674]. In Pakistan, the electricity potential is estimated about 1,598 GWhrs to 2,894 GWhrs [675].

It is generally expected that a sugar factory should be an independent source of energy. This implies that it should produce its own electricity and heat using available materials, mainly like filter cake, molasses, bagasse, and trash [676]. Compared to all other crops, the sugar cane crop has the highest potential for bioelectricity generation globally[662]. According to [675], one tone of cane bagasse can produce 0.450 MWh of electricity by means of traditional cogeneration technology. whose benefits include country's electricity generation capacity and generate employment opportunities in rural areas. With significant environmental benefits and economic benefits for sugar producing countries [675].

Although just 10 countries account for over 80% of sugar cane production, the crop is grown in more than 100 countries globally [672, 677]. The electricity demand for a typical sugar factory is between 20 and 30 kwh/ton of cane processed. A typical traditional and low efficient sugar factory can produce 60 to 70 kWh/tc but modern and more efficient

sugar factories can generate between 100-130 kWh/tc operating at higher steam pressure of up to 88 bars [678]. Evaluation of bagasse cogeneration shows that it is as competitive as fossil fuel power plants in performance indicators [677, 679].

8.2. Modernization of Traditional Sugar Mills for Export based Power Generation

A retrofit analysis of Indonesian sugar factories showed that the upgraded CEST cogeneration system with same steam parameters used as base case plant i.e. 30 bar/340 °C but using electric drives could export 45 kWh/TC as excess electricity to the grid while a retrofit using higher steam data of 80 bar and 480 °C with electric drives increased exported electricity by 50%. In a study done in a Brazilian sugar factory having a cogeneration system with back-pressure steam turbine (BPST) at low steam parameter of 22 bar and 300°C g produced about 10 kWh/TC excess electricity. In another study at Brazilian sugar factory employing Back Pressure Steam Turbine (BPST), but at higher steam parameter of 67 bar and 480 °C, it was observed that 60 kWh/TC milled was produced as excess electricity. In a study in an Indian sugar mill applying condensing extraction steam turbine (CEST) technology at high steam parameters of 67 bar and 495 °C, it was noted that the sugar mill generated excess power in the range 90–120 kWh/TC. A study in another Indian sugar mills applying CEST technology but at steam parameters of 87 bar and 515 °C produced surplus power in the range of 130–140 kWh/TC[668, 680].

The condensing extraction steam turbine (CEST) cogeneration system has the flexibility of producing both electricity and steam for process use during the crop season and electricity alone during the off crop season when process steam is not needed. [668].

The modern sugar mills are generally equipped with condensing extraction steam turbine (CEST) turbine technology, which can generate surplus power while supplying extracted steam for process applications. To ensure that steam is maximally applied for power generation, modern sugar mills make use of electrical drives in place of steam turbines for mechanical power applications in driving, mills, fans, and other devices in the sugar factory. Diffusers which need less mechanical power are also used in place of mill rollers for juice extraction from sugar [668].

The most common strategy used to generate more electricity for sale to the grid in the transition by the sugar mills to the use of more efficient cogeneration systems consisting of high pressure and temperature steam Rankine cycle cogeneration systems which are currently matured cogeneration systems currently applied in countries like Brazil, India and Mauritius[655, 681]. By reducing steam consumption in the processes, exergy destruction reduces the production of sugar and ethanol but with an increase in exergy loss related to a greater amount of excess bagasse used. The net effect is higher exergy-based costs for sugar and ethanol in sugar factories producing ethanol in addition to sugar[655].

Table 8-1 shows heat to power ratios and typical efficiencies for selected methods for cogeneration in the sugar cane industry. Modernization requires the reduction of heat to power ratio.

Table 8-1: Heat to power ratios and efficiencies of cogeneration unit

	Cogeneration system	Heat to power ratio	Electrical efficiency (%)	Total energy efficiency (%)
1	Back pressure steam turbine	4-14.3	14-28	84-92
2	Extraction condensing turbine	2-10	22-40	60-80
3	Gas turbine	1.3-2	24-35	70-85
4	Combined cycle	1-1.7	34-40	69-83
5	Reciprocating engine	1.1.-2.5	33-35	75-85

From Table 8-1, it is noted that the back pressure steam turbine has the lowest electrical efficiency but does not necessarily lead to lower overall energy efficiency. However, they have the lowest electrical efficiency and heat to power ratio and therefore are not appropriate where maximum electricity generation is the objective.

It is noted that as the heat to power ratio increases, the corresponding electrical efficiency decreases regardless of the higher total energy efficiency (60%-90%). To achieve higher efficiency, there is a need to improve the turbine inlet conditions. The traditional mills generally have inlet steam at 20-30 bar and 300-400 °C, but more efficient modern cogeneration factories operate with boilers steam inlet pressure of 45-80 bar and 100 bar in some cases and over 450°C steam temperature[311].

8.3. Feasibility of Bagasse Cogeneration

8.3.1. Bagasse Cogeneration at Nzoia Sugar Company Ltd.

8.3.1.1. Overview

This section contains work published in [45, 551] on feasibility of bagasse cogeneration by a 3000 TCD sugar factory called Nzoia Sugar Company. Ltd. The sugar industry has significant energy potential that can be exploited to sustain the industry and contribute to the energy transition. In this study, the electricity generation potential of a 3000 TCD factory (tons of cane per day crushing capacity factory) was analysed. The sugar industry is highly competitive and is characterised by high costs of production making diversification into power generation necessary to increase its competitiveness. Diversification into export power generation by sugar factories will improve the sustainability of the sugarcane industry and the electricity grid through supply of green electricity and which earns extra revenue from electricity sales. This study showed that Nzoia Sugar factory which is a traditional factory has electricity generation potential of about 15 megawatts (MW) based on a continuous power plant design. This may not be realized currently due to challenges like low factory availability due to breakdowns and shortage of sugarcane for milling and high steam to power ratio. The plant uses old inefficient equipment like boilers and turbines and uses steam turbines as prime movers for cane knives and mills which increases the steam to power generation ration. These can be improved by conversion of turbine prime movers to more electric drives, replacement of the old boilers and steam turbines, use higher steam pressure boilers and turbines, use more efficient extraction condensing turbines and reduce process steam requirements through process improvements.

8.3.1.2. Performance Analysis of the Factory

Nzoia Sugar Company Limited located in Western Kenya was incorporated on 1st August 1975 under the Companies Act as a limited liability company with the Government of Kenya owning 98% of shares, while 2% was shared by Five Cail Babcock of France (FCB) and Industrial Development Bank (ADB). The company had initial cane milling capacity of 2,000 tonnes of cane per day (TCD) which was increased in 1986 to 3000 TCD with optimum sugar production of 315 tons per day. The planned capacity is 7000 TCD and 735 tonnes of sugar per day was abandoned due to financial constraints facing the miller [682].

8.3.1.3. Milling and Electricity Generation

The performance of the factory based on the factory production records are as summarised in Table 8-2.

Table 8-2: Current condition of power generation in Nzoia Sugar Company [682]

Parameter	Rate/Value
Daily bagasse production	1040 tones
Usage (bagasse)	800 tones
Current availability of bagasse	Available
Daily cane availability	Available
1 Water-tube fixed grate boiler 25 bars 330°C	54 tones/hr.
2 FCB water tube boiler 23bar 320°C	27 tones/hr. each
Number of boilers	3
Average age of the boilers	39 years old
Efficiency of the boiler	60%

Optimum capacity	Operating capacity	3 MW
Domestic Consumption		2.8 MW
Export to the grid		0
Steam Pressure Range		20 -25 bars
Current operation of the plant		Operational

Table 8-2 shows the current condition of power generation in Nzoia Sugar Company. It is noted that the factory has got 3 boilers of capacity 108 tons/hr aged over 39 years with average bagasse consumption rate of 54 tons per hour and thermal efficiency of 60%. The plant consumes 76.9 % of bagasse produced during steady continuous milling hence a bagasse build-up of 24.1% indicating excess bagasse and wastage of useful energy resource for power generation. With very old and obsolete energy system equipment like boilers and turbines, the energy efficiency is extremely low.

The power plant design and operation parameters are shown in Table 8-3.

Table 8-3: Operational conditions Quantity and Units

Operational conditions	Quantity	Units
Sugar cane crushed/year	402740.89	tc
Sugar cane crushed/hr (Design capacity)	125	tc/h
Amount of bagasse produced (Average)	13.8	t/h
Steam produced	108	t/h
Steam pressure (Average)	22	Bar(g)
Steam temperature (average)	300	°C

Steam at pressure-reducing valve	10-15	t/h
Power consumed by plant	2.8	MW
Effective operation days in one year	275	Days

Table 8-3 shows quantities and units for various energy and power system parameters including steam produced and steam pressure, steam temperature, power consumed by the plant, among others. The data shows that process operations take 10 to 15 tons/hr of steam from boilers which is up to 14% of steam generation.

8.3.1.4. Turbines

Steam turbines are important energy system devices since they generate power through steam expansion while the exhaust or extracted steam from the steam turbine in the sugar factory is used for process heating requirements[59, 101, 299]. The specifications of the steam turbines in the powerhouse are shown in Table 8-4.

Table 8-4: Turbine technical data

Parameter	Dresser Rand	Kessel (Multistage)	FCB turbine operational	Not
1 Output	3MW	4MW	0	
2 Normal Speed	5400/1135rpm	6480/1135 rpm	-	
3 Trip Speed	5400-5300rpm	6480-6000 rpm	-	
4 Steam Pressure	23Kg/cm ² g	25 kg/cm ² g	23Kg/cm ² g	
5 Steam Temperature	300-330°C	300-360°C	300-330°C	
6 Exhaust Pressure	1.5Kg/ cm ² g	1.5 kg/ cm ² g	1.5Kg/ cm ² g	

Table 8-4 shows specific characteristics of turbines used at the powerhouse of Nzoia Sugar Company Ltd. These parameters include output power, normal speed and temperature, power rating and specific steam consumption, among others. The two operational turbines have installed capacity of 7 MW against effective capacity of 2.8 MW (40% of installed capacity) and excess capacity is 5.2 MW (60%).

8.3.1.5. Sugar Factory Performance Analysis

The factory experiences variable performance based on the state of the mill and availability of sugar cane for milling and hence availability of bagasse for steam and electricity generation.

Table 8-5: Table of sugar produced and cane crushed over years at Nzoia Sugar Company [671]

Year	Sugar Produced (TS)	Cane Milled (TC)
2009	68254	679568
2010	65859	645591
2011	61886	652170
2012	64669	690996
2013	55535	680364
2014	49648	596186
2015	86821	924721
2016	59218	706173
2017	46724	580868

From Table 8-5, it is noted that milling generally varies from 580,868 tons of cane per year to 924, 721 tons of cane per year. This is summarised in Figure 8-1.

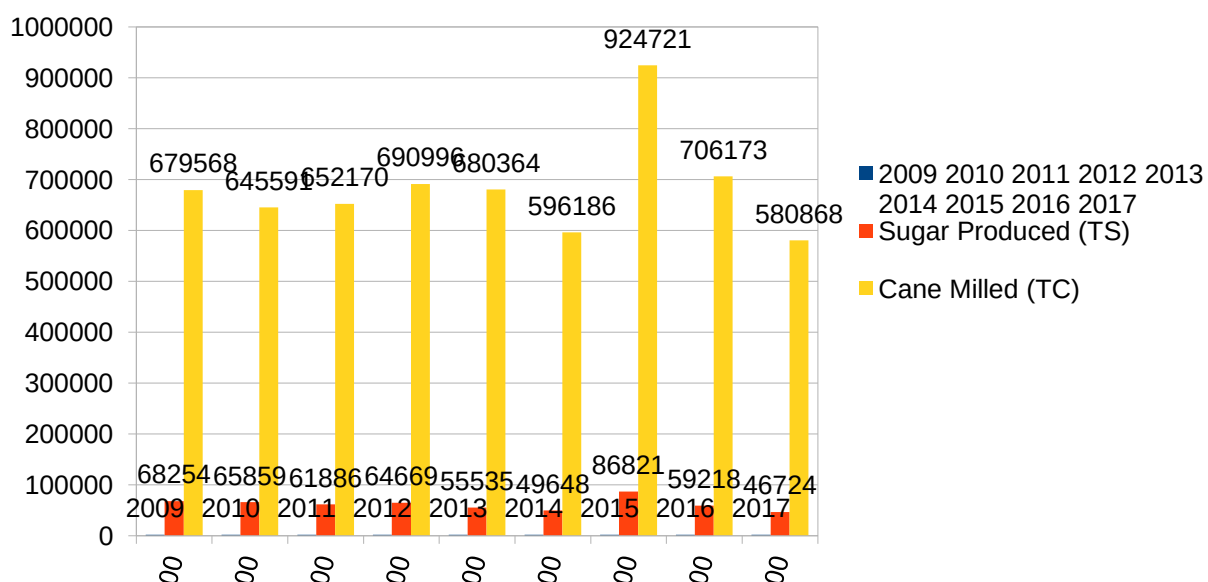


Figure 8-1: Cane and sugar production by Nzoia Sugar Company Ltd.

From Figure 8-1, it is noted that the highest sugar production between 2009 and 2017 was realised in the year 2015 with the lowest sugar production in 2017. The annual production varied from year to year.

8.3.1.6. Results and Discussion

This study shows huge energy generation and efficiency opportunities in the traditional sugar factories which should be improved through modernization of the plants. Cogeneration by the sugar mills can be improved by measures like increasing biomass supply by harvesting and transporting cane trash i.e. sugar cane tops and leaves. Optimum power generation by the sugar industry will be achieved by establishing an enabling state-of-the-art continuous and firm power plants for sugar factories with emphasis on energy efficiency to minimize energy consumption and maximize generation and export of excess cogenerated electricity to the grid. Since many sugar cane producers worldwide face economic challenges, sugarcane bagasse cogeneration can boost the sugar industry by providing an extra, stable revenue stream will enhance the competitive position of sugar manufacturing factories.

For Brazil and other ethanol from sugarcane producing countries from the sugar industry as a petroleum substitute, enhanced sugar factory efficiency will reduce the cost of ethanol which would accelerate the rate of fossil fuel substitution as international oil prices remain high [661].

A performance analysis of the current cogeneration plant at Nzoia Sugar factory indicates wasteful use of energy and hence the need to optimize generation and use and develop a more efficient power plant for export of power to the grid while meeting domestic factory operations electricity demand. Any maintenance or failure of the turbine means disrupting power production process since the optimum capacity is just 4 MW which is hardly sufficient to meet the entire factory electricity needs. The current power plant design is meant to maximize combustion of bagasse as a disposal method while generating just enough steam and electricity for factory operations. With high ratio of cane crushed TC/TS means the bagasse has significantly high sugar content which causes undesirable clinkers in the boiler furnace during combustion of bagasse. The clinkers reduce boiler performance and efficiency[64, 81, 326].

The old and obsolete boilers and turbines also call for replacement with more efficient equipment for steam and power generation while the prime movers like cane knife and mill turbines ought to be replaced with electric drives to reduce factory steam use and concentrate on power generation. The use of variable drives and right sizing of electric drives will also reduce factory electricity demand to avail more electricity for grid export. The bagasse moisture content is also relatively high which affects the fuel heating value and hence boiler as well as power plant efficiency hence to need to overhaul the milling process to reduce bagasse moisture content to the level of 48 to 50% moisture content from the current average of 52%.

As a fuel, bagasse has got that the average universal gross calorific value of dry bagasse is (GCV) is about 19,488 kJ/kg of dry bagasse. Given that dry bagasse has 6-7% moisture content, a working average of 6.5% moisture gives net calorific value of NCV = 17,850 kJ/kg. Conversion of steam turbine driven systems to electric driven systems will avail more steam for electricity generation and hence greater power plant capacity.

There are three basic power plant configurations based on plant design and installed capacity. These are.

- i. Intermittent generation where electricity generation is not continuous and is based on sugar production needs.
- ii. Continuous power plants which are expected to operate continuously during the sugarcane crop season.

- iii. Firm power plants which are designed to operate throughout the year generally for an average of 300 days except for 65 to 66 days during which the power plant is under maintenance.

With milling capacity of 580,868 tons of cane per year to 924, 721 tons of cane per year, the factory can develop a continuous power plant with electricity generation potential of 60 kWh per ton of cane milled. It should however invest in boilers of pressure 30 bars to 40 bars and capacity average of 120 tons/hr. For maximum electricity export, the mill turbine and cane knife drives should be converted to electric drives to avail more steam for power generation reduce internal electricity consumption to below 30% of total generation, install condensing extraction turbines of capacity 15 MW on average and improve plant availability and load factor to about 90%.

8.3.1.7. Conclusions

The sugar industry has significant electricity generation potential using bagasse as a fuel for steam generation. Nzoia Sugar factory with sugar cane milling capacity of 3000 TCD has electricity generation potential of about 15 MW based on the continuous power plant configuration. This cannot be achieved currently because of poor factory availability mainly caused by factory breakdowns and shortage of sugarcane for milling. The plant should increase its availability to about 90% for steady milling and electricity generation to realise its electricity generation potential. The steam to electricity ratio should also be reduced by minimising steam consumption in process heating and conversion of steam turbine prime movers to more efficient electric drives. This will release steam for use in electricity generation. Replacement of the old and inefficient boilers with new efficient boilers of greater pressure and efficiency will position Nzoia Sugar Company Ltd. for export electricity cogeneration. Replacement of the back pressure steam turbines with more efficient condensing extraction turbines will also increase power output.

8.3.1.8. Recommendations

The industrial sector should explore energy efficiency measures to reduce their energy demand and exploit ant opportunities like cogeneration so that they embrace decentralised generation to produce enough energy for their internal use and export excess to the grids. This requires financing, investment in technology and decentralised generation infrastructure. These will

improve their socioeconomic viability while contributing to the global energy transition.

8.3.2. Bagasse Cogeneration at Mumias Sugar Company

8.3.2.1. Overview

The content of this section is published in paper [57] co-authored by Prof. Oludolapo whose overall objective was to establish the feasibility of export-based cogeneration by a leading sugar factory in Kenya which presents the practical challenges of bagasse based grid power generation by sugar factories. It was established that the sugar factory invested in a 38 MW cogeneration power plant to export 26 MW as excess electricity to the national grid, with the balance being used for the factory internal energy needs. The cogeneration plant initially operated profitably by selling electricity to the Kenyan grid, but reliance on bagasse alone as the fuel placed the plant at the mercy of the sugar factory's intermittent operations due to breakdowns and unreliable supply of sugarcane to sustain continuous operation of both the sugar factory and the power plant. The study showed that after three years of profitable operation, power plants became unsustainable and hence stopped the export of power. The power plant faced challenges like low load and capacity factors occasioned by unreliable milling of cane. This meant irregular bagasse fuel supply to the power plant hence capacity underutilization and availability of the plant which attracted huge fines and penalties from the utility company and eventual disconnection from the grid that sent the factory into financial receivership. The study recommends policy initiatives to encourage export of electricity from the sugar industry while development of multi-fuel plants will delink the co-generation from the challenges of sugar cane factory operation. These measures will improve the power plant availability, load factor, capacity factor and reliability ultimately making bagasse cogeneration suitable for base load grid electricity supply while creating an extra revenue stream for the sugar factories.

8.3.2.2. Introduction

The idea of Mumias Sugar Company Ltd started in 1967, when the Government of Kenya commissioned Booker Agriculture and Technical Services to do a feasibility study on the viability of growing sugarcane in Mumias area of western Kenya and then initiate a pilot project. The relative remoteness of the area and poor communication prevented the development of an active market economy. The study showed that it was possible to establish

a viable sugar scheme at Mumias where the factory is supplied with cane from both the Nucleus Estate and indigenous farmers. This led to the incorporation of the company on the July 1, 1971, as Mumias Sugar Company to implement the project with the Government of Kenya holding 71% majority shares and minority interests held by the Commonwealth Development Corporation (17%), Kenya Commercial Finance Company (5%), Booker McConnell (4%) and the East African Development Bank (3%). The company's original capacity of the factory was 45,000 tons of sugar per year when it was fully operational in 1973. In 1979, the capacity was increased to 3000 TCD and in 1997 factory rationalization was completed and daily milling capacity increased further to 7,000 tons of cane per day (TCD) and the efficiency of sucrose extraction was raised from 82% to 86% through factory modernization. With steady operations and need to diversify the product base and expand the market visibility, in 2000 a nationwide distribution network for sales and marketing was established and an electricity sale agreement with Kenya Power and lighting Company to supply 10, 000MWh of electricity per annum to the national grid was concluded. These enabled Mumias to diversify into export cogeneration.

In 2006, an agreement was signed with Avant Garde Engineers and Consultants (P) Ltd of India to develop US\$ 40 million power production unit, to increase generation capacity of the factory 38 MW of which 26 MW was for export to the National Grid and the balance for domestic or factory consumption. This shows that, it is through prudent management and good company performance that Mumias Sugar Company Ltd. [81].

The factory's cogeneration plant operated profitably but due to inability to get constant supply of cane for factory milling and hence bagasse for cogeneration, Mumias suffered huge penalties as per the power purchase agreement with Kenya Power that finally led the utility company into switching off power supply to Mumias. This move triggered a crisis that saw the miller stop operations and was finally placed under receivership at the time of this study. The purpose of this study is to establish the performance of the cogeneration plant and identify the potential and challenges of bagasse cogeneration in supply of grid electricity.

8.3.2.3. Cogeneration Power Plant Capacity

The main objective for establishing the 38 MW bagasse cogeneration plant by Mumias Sugar Company was to make use of excess bagasse fuel to generate extra power for sale to grid and

earn an extra revenue stream in addition to sugar sales. Selling surplus power to the national grid contributed to Kenya's efforts of achieving self-sufficiency in electricity generation and supply. The plant was also to help eliminate the cost of disposing off excess bagasse and its effects to the environment. The 38 MW cogeneration plant was commissioned in May 2009 which led to increased internal electricity demand from 10 MW to 12 MW but excess electricity for sale to the grid increased from 3 MW to 26 M at a cost of \$ 40 Million dollars' loan capital.

8.3.2.4. Cost of Cogenerated Power

The unit cost of the cogenerated electricity based on both export and installed capacity of the power plant is computed below based on the power plant loan capital.

- i. The unit cost of the export capacity is $\$40,0000,000/26,000 \text{ kW} = \$ 1,538/\text{kW}$
- ii. Based on the total capacity of the cogeneration plant, the unit cost is $40,000,000/34,000\text{kW} = \text{US } \$ 1,176 \text{ US\$/kW}$.

The assumption is that there is no other cost involved in the power plant development.

8.3.2.5. Environmental Impact

The installation of the new plant was expected to reduce carbon emissions by up to 120,000 tons per year according to the CER ratings whose rates vary between \$6 and \$20 per ton, hence extra revenue and mitigation against carbon emissions and global warming. This was a great step aimed at increasing the power production in the factory. The project was registered by the UNFCCC Executive Board as a CDM project on 1st Sept 2008.

8.3.2.6. Comparison of the Old and New Cogeneration Power plant

The comparison between the old plant and new plant is as illustrated in Table 8-6.

Table 8-6: The characteristics of the old and new cogeneration plants.

Parameters	Old Plant	New Power plant
1 Daily bagasse production	140 tons/hr.	140 tons/hr
2 Bagasse Usage	110 mt/hr.	130 tons/hr

3	Excess Bagasse (Fuel accumulation)	30 mt/hr.	10 tons/hr
4	Boilers (number)	7	2
5	Steam	220 mt/hr.	170 tons/hr (New), 110 tons/hr (old boiler)
6	Steam quality	330°C, 45 bar	New boiler (87 bar, 550°C Old boiler (330°C, 45 Bar)
7	Installed capacity	13 MW	38 MW
8	Domestic Power consumption	10 MW	12 MW
9	Excess power for export	3 MW	26 MW

The following observations are made from Table 8-6.

- i. The new cogeneration plant did not require factory capacity expansion.
- ii. Number of boilers were reduced from 7 to two by construction of a new boiler and retirement of 6 smaller old boilers.
- iii. Factory electricity demand increased from 10 MW to 12 MW due to increased auxiliary demand.
- iv. Excess electricity generation increased from excess of 3 MW to 26 MW for export.
- v. High pressure steam for factory uses and medium pressure for the cogeneration plant were generated with room for modernization and expansion of medium pressure boiler.
- vi. Excess bagasse generation and buildup reduced from 30 tons per hour to 10 tons per hour hence reduced fuel wastage.
- vii. Steam generation increased from combined capacity of 220 tons/hr to 280 tons/hr.

8.3.2.7. Power Purchase Agreement (PPA)

A power purchase agreement (PPA) is legally binding agreement between the utility company and electricity producer and contains targets and obligations for all parties in the

contract. In this case the Mumias Sugar Company has a binding agreement with Kenya Power to supply electricity. The PPA has the following provisions shown in Table 8-7.

Table 8-7: PPA specifications (Author's summary of information)

Contract Item/Parameter	Specifications
1 Contract period	10 years
2 Rate/price of power	Capacity (US cents 2.6) + Energy (US cents 3.4) =US cents 6 per kWh
3 Plant export capacity	26 MW
4 Availability	85% of the capacity
5 Operating days (Target)	275 Days per annum
6 Guaranteed Min Dispatch	90 million KWh/year 40% capacity/year
7 Amount surcharged as penalties	US \$20 cents per kWh
8 Total amount surcharged	KES. 1.1 billion

Error! Reference source not found. shows that the company is paid for exported power based on both available capacity of the powerplant and total electricity supplied to the grid and combined total of 6 US cents per kWh but with a penalty at the rate of 20 US cents for failure to supply power as per the PPA which is about 3.3 times more than the total unit price. This shows that the power purchase agreement heavily punishes failure to supply power by the sugar company.

8.3.2.8. Performance Analysis of The Cogeneration Plant

The performance of the cogeneration plant 6 years of operation between 2009 and 2015 is presented in **Error! Reference source not found..**

Table 8-8: Annual power export (GWH) by Mumias Sugar Company between 2009-2015

Years	Bagasse Production (tons)	Bagasse Used (tons)	Export in GWh	Surcharge (GWh)	Annual Revenue (\$)	Surcharge (US \$)	Net Revenue (US\$)
2009- 2010	731,000	650,000	99	10.2	5,940,000	2,040,000	3,900,000
2010- 2011	731,000	650,000	87	22.2	5,220,000	4,440,000	780,000
2011- 2012	731,000	650,000	100	9.2	6,000,000	1,840,000	4,160,000
2012- 2013	520,000	520,000	71	38.2	4,260,000	7,640,000	(3,380,000)
2013- 2014	420,000	410,000	57	52.2	3,420,000	10,440,000	(7,020,000)
2014- 2015	90,000	90,000	14	95.2	840,000	19,040,000	(18,200,000)
TOTAL	3,223,000	2,970,000	428	227.2	25,680,000	45, 440,000	(19,700, 000)

Table 8-8 shows the power generation and financial performance of the cogeneration power plant between 2009 and 2015. This is also presented in.

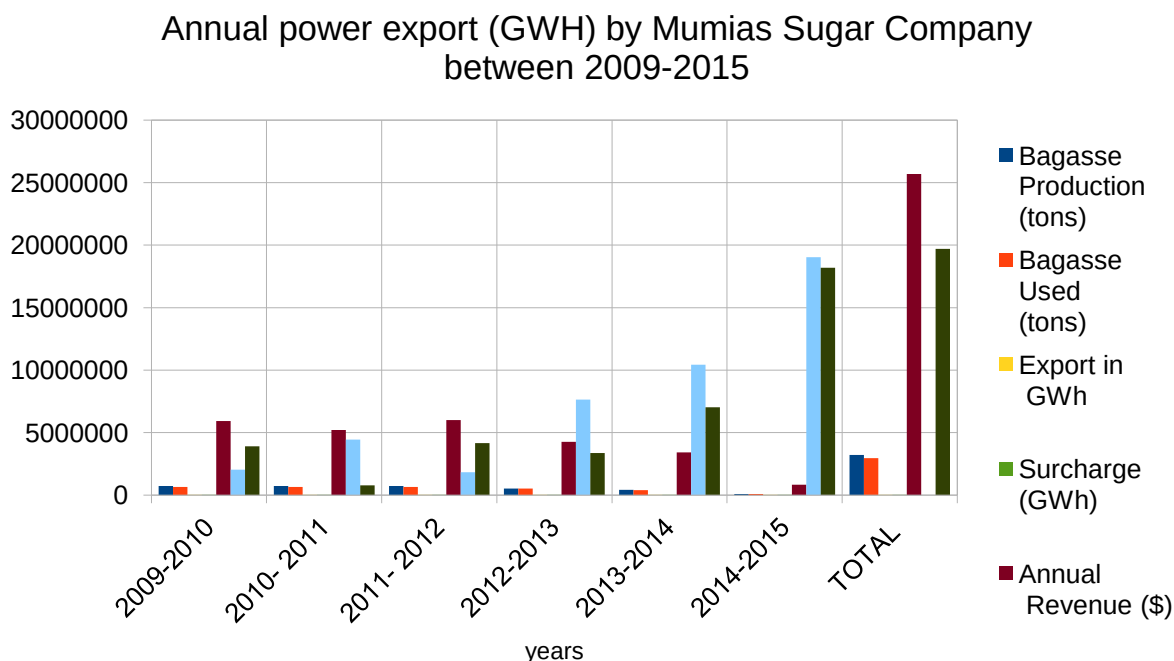


Figure 8-2: Bagasse production and electricity export by Mumias Sugar between 2009 and 2015.

From Figure 8-2 and Table 8-8, it is noted that the total electricity exported was 428 GWh, units surcharged or penalized for failure to supply to the utility amounted to 227.2 GWh, cumulative revenue earned was US\$ 25,680, 000, penalties for poor performance earned the company a surcharge of US\$ 45, 440,000 and net financial loss was US\$ 19,700,000. Continued fluctuations in the plant output made it difficult for the plant to meet the terms of agreement in the PPA. At some point the company could not export any power to the national grid at all. For the first 3 years of the power plant operation, the technical performance based on 21.5 effective capacity and 26 MW installed capacity was follows.

- i. Total generation was 286 GWh.
- ii. Average load based on agreed 285 days of operation annually is 10.8 MW.
- iii. Load factor was 0.5.
- iv. Capacity factor was 0.4.

8.3.2.9. Bagasse Supply and Electricity Generation

Bagasse is the only fuel used by the cogeneration plant since it has no secondary fuel. Availability of bagasse for power generation is a factor of the cane availability and

performance of the sugar mill. Bagasse supply is shown in figure A bar graph showing the total amount of bagasse supplied to the plant annually is presented in Figure 8-3.

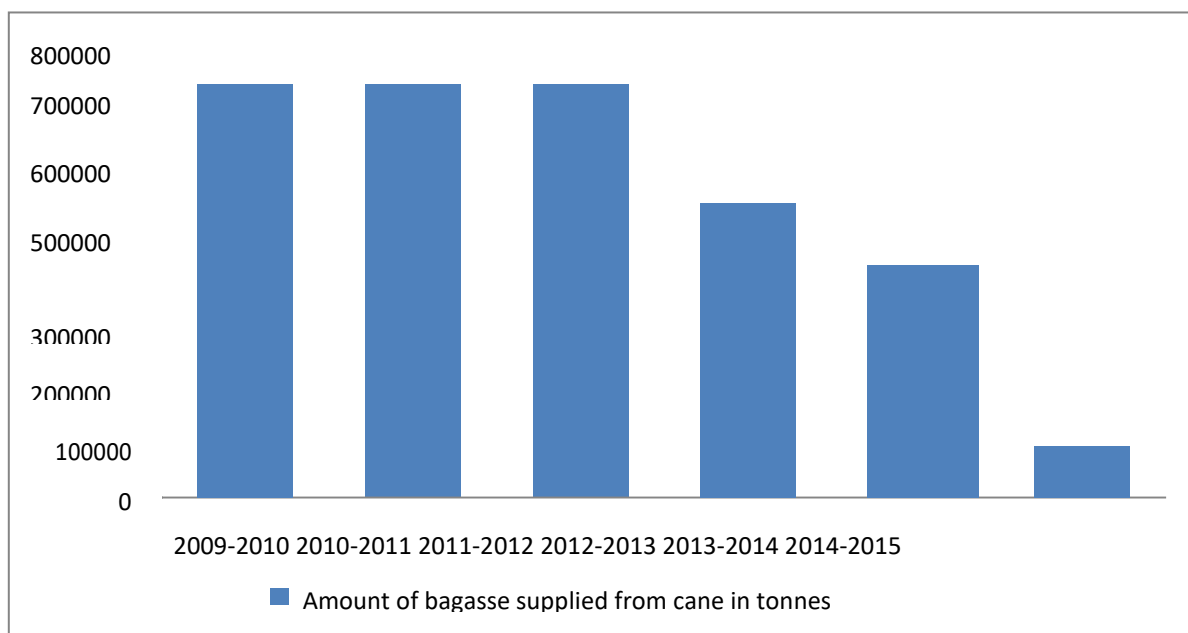


Figure 8-3: Bagasse supply between 2009 and 2015.

From Figure 8-3, it is noted that enough bagasse was supplied to the plant during the first three years after which the supply began to reduce significantly. The reduction in the amount of bagasse supplied continued to reduce from 2012 until 2015 as indicated when only less than 100,000 tons of bagasse was supplied during the whole year. The plant was designed to burn more than 100 metric tons of bagasse per hour at its optimum performance. However, due to insufficient supply of bagasse, it could not run at its optimum anymore. Reduced power output led to reduced power exported to the national grid and hence reduced revenue generation from power export to the Company.

The bagasse cogeneration plant is also designed such that it operates on just one, but high-volume boiler that runs on a single-high-capacity furnace. The generated steam is used to drive a single turbine. The turbine is large enough and can generate as high as 34 MW of power. The fact that the massive plant runs on a single furnace, single boiler and a single prime mover makes it very difficult to control the costs involved in its operation. For example, the costs involved in generating 10 MW and 34 MW are no different since at both low and high output levels the plant operates at constant conditions. It is, therefore, uneconomical

running the plant at lower output considering the heavy initial investment involved in setting it up. Whenever there occurs a break down or damage of part, however minor, the entire plant must be shut down for repairs to be done unlike other power plants that are made up of several units. This means that the plant cannot generate power at all during both repair and maintenance periods. The plant is, therefore, unavailable during such times and hence unreliable in supplying power to the national grid. Figure 8-4 shows the gross revenue from sold electricity.

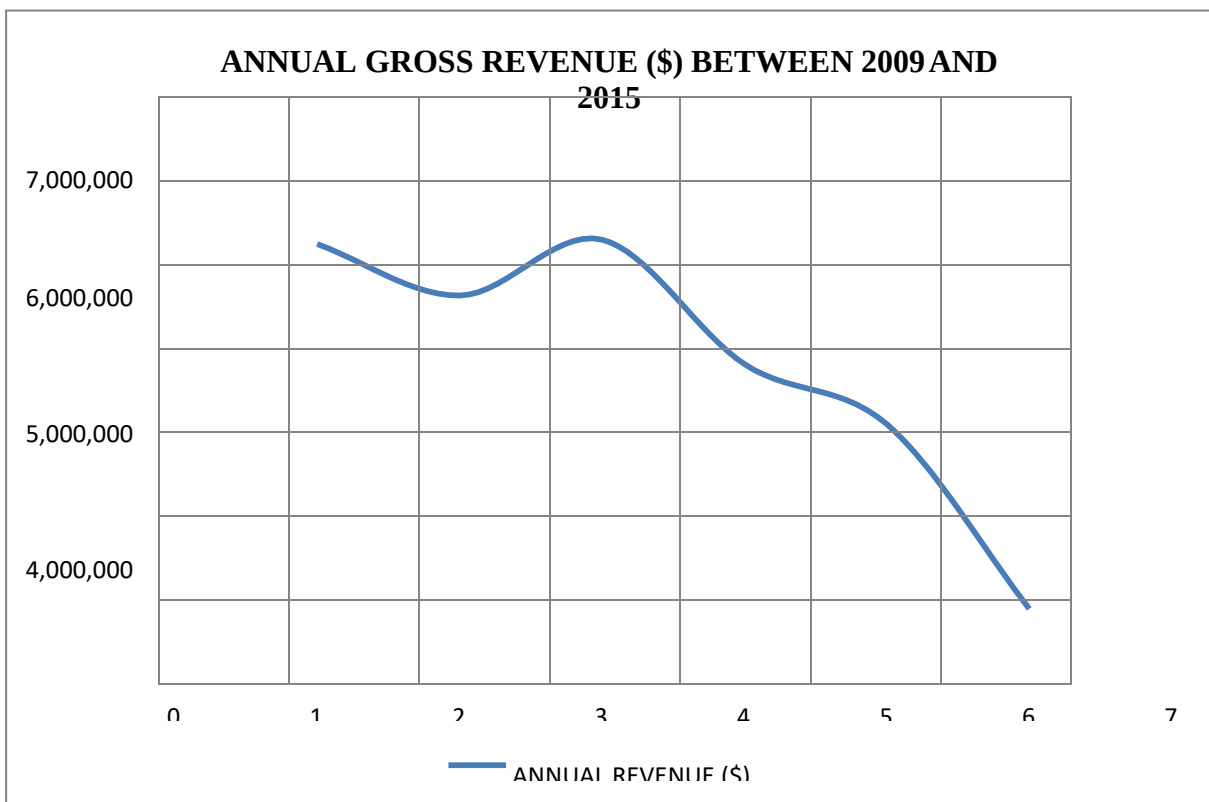


Figure 8-4: A graph of annual net revenue between 2009 and 2015

Figure 8-4 shows the annual gross revenue for 2009-2015. It is noted that in the first three years, between 2009 and 2011, the Company recorded annual revenue of \$5-\$ 6 million. However, beginning 2012 the annual revenues began decreasing drastically and consistently until 2015 when the lowest amount was recorded. In the first three years of operation, the Company made profit out of the generated and exported power. Later, beginning 2012, the Company began making losses. The number of losses made increased significantly down to

2015 when it made a loss of more than \$ 18 million. The cogeneration plant is currently experiencing a financial crisis as there is no revenue collected since no power is being exported to the national grid.

8.3.2.10. Contribution to the National Electricity Grid

The Kenyan electricity grid receives power from various generating power stations with most of the power received from the Government controlled Kenya Electricity Generating Company. Most Independent Power producers own and generate diesel power plants while Mumias is the only company that supplied power from sugar industry cogenerations. Other sources of grid electricity are geothermal, hydro power stations, and wind energy[683-685].

Company	Capacity (MW) as at 30.06.2015		Energy Purchased in GWh					
KenGen								
	Installed	Effective	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15
Olkaria I 4 & 5	140	140						744
Geothermal Total	488	480	939	1,081	1,106	1,096	1,156	3,104
Wind:								
Ngong	25.5	25.5	16.3	17.7	14.6	13.9	17.6	37.7
KenGen Total	1,596	1,534	3,606	5,040	5,409	5,968	5,931	6,943
Government of Kenya (Rural Electrification Programme)								
Thermal	18	14.5	19	21	23	26	29.8	35.1
Solar	0.569	0.569			0.3	1	0.8	0.9
Wind	0.55	0.2			0.1	0.7	0.4	0.003
Total Offgrid	19	15	19	21	23	27	31	36
Independent Power Producers (IPPs) - Thermal & Geothermal								
Iberafrica I&II	108.5	108.5	621	722	705	592	550	198
Tsavo	74	74	495	368	283	178	152	83
Thika Power	87	87					454	233
Mumias - Cogeneration	26	21.5	99	87	100	71	57	14
OrPower 4 - Geothermal I, II & III	110	110	400	372	392	503	851	955
Rabai Power	90	90	318	394	338	443	633	609
Imenti Tea Factory (Feed-in Plant)	0.3	0.3	0.3	0.4	0.8	0.7	0.1	0.5
Gikira small hydro	0.514	0.514					0.4	1.6
Triumph Diesel	77	77						5
Gulf Power	80.32	80.32						60
IPP Total	654	649	1,933	1,945	1,820	1,788	2,698	2,160
Emergency Power Producers (EPP)								
Aggreko Power	30	30	1096	267	381	261	93.8	62.7
EPP Total	30	30	1,096	267	381	261	94	63
Imports								
UETCL			37	30	36	41	83	76
TANESCO			1.1	1	1.1	1.2	1.3	0.6
EEPCO							2.1	2.8
Total Imports			38	31	37	42	87	79
System Total	2,299	2,228	6,692	7,303	7,670	8,087	8,839	9,280

shows the various sources of grid power between 2009 and 2015.

Company	Capacity (MW) as at 30.06.2015		Energy Purchased in GWh					
	KenGen							
	Installed	Effective	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15
Olkaria I 4 & 5	140	140						744
Geothermal Total	488	480	939	1,081	1,106	1,096	1,156	3,104
Wind:								
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KenGen Total	1,596	1,534	3,606	5,040	5,409	5,968	5,931	6,943
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TANESCO			1.1	1	1.1	1.2	1.3	0.6
EEPCO							2.1	2.8
Total Imports			38	31	37	42	87	79
System Total	2,299	2,228	6,692	7,303	7,670	8,087	8,839	9,280

Figure 8-5: Electricity generation in Kenya from different sources between 2009 and 2015

From

Company	Capacity (MW) as at 30.06.2015		Energy Purchased in GWh					
KenGen								
	Installed	Effective	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15
Olkaria I 4 & 5	140	140						744
Geothermal Total	488	480	939	1,081	1,106	1,096	1,156	3,104
Wind:								
Ngong	25.5	25.5	16.3	17.7	14.6	13.9	17.6	37.7
KenGen Total	1,596	1,534	3,606	5,040	5,409	5,968	5,931	6,943
Government of Kenya (Rural Electrification Programme)								
Thermal	18	14.5	19	21	23	26	29.8	35.1
Solar	0.569	0.569			0.3	1	0.8	0.9
Wind	0.55	0.2			0.1	0.7	0.4	0.003
Total Offgrid	19	15	19	21	23	27	31	36
Independent Power Producers (IPPs) - Thermal & Geothermal								
Iberafrica I&II	108.5	108.5	621	722	705	592	550	198
Tsavo	74	74	495	368	283	178	152	83
Thika Power	87	87					454	233
Mumias - Cogeneration	26	21.5	99	87	100	71	57	14
OrPower 4 - Geothermal I, II & III	110	110	400	372	392	503	851	955
Rabai Power	90	90	318	394	338	443	633	609
Imenti Tea Factory (Feed-in Plant)	0.3	0.3	0.3	0.4	0.8	0.7	0.1	0.5
Gikira small hydro	0.514	0.514					0.4	1.6
Triumph Diesel	77	77						5
Gulf Power	80.32	80.32						60
IPP Total	654	649	1,933	1,945	1,820	1,788	2,698	2,160
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EEPCO							2.1	2.8
Total Imports			38	31	37	42	87	79
System Total	2,299	2,228	6,692	7,303	7,670	8,087	8,839	9,280

, it is noted that KenGen has the largest installed capacity in 2016 with 1596 MW installed capacity and effective capacity of 1534 MW (96.1%) from various energy sources out of total installed capacity of 2299 MW and effective capacity of 2228 MW of which Mumias cogeneration plant had installed capacity of 26 MW and effective capacity of 21.5 MW (82.7%).

Mumias Sugar Company has electricity export installed capacity of 26 MW with effective capacity of 21.5 MW. Its electricity exports as shown in figure were 99 GWh, 87, 100, 71, 57 and 14 GWh between 2009 and 2015 averaging 73.3 GWh per annum. This amounts to load factor of 39.2%. The average contribution to the grid power for the same period was 1.5%, 1.2%, 1.3%, 0.9%, 0.6% and 0.2% which results to average contribution of 0.7% to the national electricity grid. The contribution kept on reducing due to annual increase in electricity demand while the capacity of the cogeneration plant kept reducing mainly because of deterioration in sugarcane. Production and hence fuel supply to the power plant.

The cogeneration plant performance can be summarized as follows based on agreed 285 days per year.

- i. Average load factor for the 6 years of operation is $\text{Generation / Expected maximum generation based on effective load capacity of 21.5 MW} = 428/883 = 0.48$
- ii. Average capacity factor is 0.46 for the six years based on 26 MW capacity.

8.3.2.11. Challenges Facing Mumias Sugar Company

As a result of deteriorating operational inefficiencies at the factory, the company incurred large debts that reached KES 12 billion (USD 12 million). This rendered the company unable to fund its operations and purchases. This discouraged investors and scared away stakeholders who play a very important role of funding the operations. Delayed payments to farmers for cane deliveries forced them to supply cane to other millers as others abandoned cane farming cutting off about 80% of the cane required by the factory for full-scale operations. This paralyzed operations with penalties from utilities further compounding the problem due to failed supply of contracted power. This forced the utility to cut off power supply bringing operations of the entire company including the ethanol plant to halt and eventual receivership hence collapse of the cogeneration powerplant too[57].

8.3.2.12. Findings From the Study

The following are major findings from this study.

- i. The boiler efficiency is 60%, these provides room for further improvement through design and operations. To efficiencies greater than 70%
- ii. One boiler is operating at 45 bar 330°C compared to the new boiler at 87 bars. Need to redesign the sugar factor to use high pressure boilers.
- iii. The performance of the cogeneration plant is dependent on the performance and operation of the sugar plant hence need to improve the cane sugar supply chain and factory efficiency.
- iv. Equipment inherited from the old power plant are old with most of them being older than 10 years which affects reliability and performance of the power plant.
- v. The factory and hence power plant has planned maintenance of 90 days per year hence 275 days for generation. This provides an opportunity to apply modern maintenance techniques to reduce the downtime and supply more power.

- vi. After three years of operation, the cash flow from the cogeneration plant seriously diminished due to low milling and hence low bagasse fuel supply for electricity generation leading to higher penalties than revenue. These made operation and plant maintenance impossible.
- vii. The average load factor is 0.46 while capacity was 0.48 which are below average.
- viii. The power purchase agreement between the sugar factory and the utility company heavily penalized the powerplant unavailability regardless of the sources which was unsustainable with challenges in cane supply and milling.

8.4. Conclusion

Bagasse cogeneration is a feasible investment technically and financially, but its operation and sustainability are influenced by the main sugar mill and sugar cane supply chain. The bagasse cogeneration project in Mumias Sugar Company became unreliable after the company started facing sugar cane supply challenges that caused unsteady sugar cane milling and hence unsteady supply of bagasse fuel to the power plant. The problem was further compounded by a punitive power purchase agreement where failure to supply was penalized at a rate more than double the selling price of electricity to the utility company. Therefore, the single fuel mode of operation was the main technical limitation of the of the cogeneration plant design. Multi-fuel boilers running on more than one fuel could guarantee continuous power generation since sugar cane supply is not reliable and sustainable. A friendly power purchase agreement and a flexible grid to contain frequent supply interruption is another strategy that will encourage bagasse cogeneration by sugar factories.

The research showed that initial availability of the plant was established to be about 75% which is still low compared to availability and load factors for geothermal and conventional power plants which often have availability factor of more than 0.9. This implies that the power plant had poor capacity utilization and hence wasteful. It therefore goes without saying that for any hope to be restored in the bagasse cogeneration sector, effort should be made to raise the plants availability to the recommended range of 98-99% or develop a resilient grid that can handle intermittent power generation. The idle time of the bagasse cogeneration plant stood at about 90 days per annum or 24.7% for the period under investigation, mainly because of reliance on the sugar factory operations which must be stopped weekly for maintenance and

with a month long off the crop maintenance. This down time extremely high because every minute lost is money lost and caused grid stability challenges due to limited capacity to the public grid. It is therefore important that the amount of the plant's idle time be scaled down to manageable levels. This will help raise the bagasse cogeneration plant availability and consequently raising the revenue returns.

On quality of bagasse fuel, the study showed that the moisture content of bagasse used is relatively high at an average of 52%, 2-4% higher than the recommended values of 48-50%. It is therefore important that a more effective method of drying bagasse before using it in the boilers be established to help reduce the moisture content further thereby raising the calorific value per unit mass of the fuel. Alternatively, mill setting in sugar processing should reduce moisture content to recommended range of 48-50%. It was also noted that technical personnel had challenges in operating and handling of the plant leading to longer downtimes and penalties from the utility company. The plant automation systems were not fully adopted because of lack of required skill while a number of tasks like what should be simple repairs and maintenance subcontracted or outsourced hence higher costs.

8.5. Recommendations

The original design of the plant should be reviewed to allow the use of other alternative types of fuel e.g. coal to help to supplement the main fuel i.e. bagasse when it runs out for any reason like breakdown in the sugar mills or disruption in sugar cane supply for mill. This will help to maintain the cogeneration plant running and generating power during times of both availability and unavailability of bagasse in the factory. A 34 MW turbine generator is too big as a single unit and does not provide desired flexibility in generation with varying supply of bagasse and maintenance requirements. Flexibility will allow the factory to operate almost independent to the power plant and less interruption to generation should occur due to interruptions in factory operations and vice versa. These can be achieved by having multiple units and a secondary fuel like coal or gas.

The supporting policy framework is needed to exploit the immense energy potential of sugar factories e.g. an attractive feed in tariff and flexible power purchase which recognizes the challenges like raw materials supply interruptions and appropriate infrastructure that supports decentralized generation. Governments and regulators should formulate and implement

favorable policies that govern cogeneration prohibitive penalties like those imposed on Mumias Sugar Company for genuine challenges and inability to meet the targets should by treating such power plants as non-dispatchable sources just like wind and solar.

Farmers, as major stakeholders in sugar industries, should be motivated and encouraged to grow and supply cane to the sugar factories through incentives like good pay per tonnage, timely making of payments upon cane delivery and payment for both sucrose and fiber content in cane since both are valuable with export cogeneration in place to increase their revenue and encourage them to grow sugarcane.

The traditional sugar factories should be modernized to increase their energy efficiency and power generation capacity by reducing internal factory energy needs and minimizing wastage. The energy efficiency measures include electrification and automation of operation, replacement of fixed drives with variable speed drives, replacement of low and medium steam boilers and turbines with more efficient high pressure and temperature[45, 57, 59, 64, 296, 326, 551].

CHAPTER 9:

GEOTHERMAL WELLHEAD POWER PLANTS IN THE ENERGY TRANSITION

9. Overview

The contents of this chapter are published in the authors publications presented as references [44, 58, 206, 347, 393, 394]. Although geothermal resources are huge, the deployment of geothermal power plants is limited by huge upfront costs and risks hence the limited share of geothermal in global electricity generation. Wellhead generators are modularized units installed on the well pad as soon as a well is drilled and tested which cuts down the waiting period before a central power plant is developed upon drilling multiple wells.

9.1. Introduction

Geothermal energy has a significant role to play in the global transition to renewable and low-carbon energy systems because of its ability to supply steady and flexible electricity particularly for baseload demand because of its cost competitiveness compared to fossil fuel energy options. However, geothermal faces a challenge of long project development times with conventional power plant taking an average of 5–10 years and with high risks associated with drilling of unproductive wells which discourage private investment and quick deployment. Although geothermal energy has a huge potential for power generation, it currently contributes less than 1% of global electricity generation capacity.

The generation capacity grew from 8.7 GWe in 2005 to 15.61 GWe at the end of the year 2020, representing average annual growth of 4.01%. The overall objective of this study was to determine the potential, features and application of wellhead power plants in electricity generation both to complement and substitute central powerplants. It was established that wellhead power plants can be used on temporary basis during the project development or permanently as grid connected or off grid generation facilities. With current technology, wellhead generators of up to 15 MW capacity can be installed on well pads of production wells for temporary or permanent electricity supply.

Wellhead generators can facilitate optimum resource utilization especially for wells with unique conditions like too high or too low pressure and temperature compared to others in the

same steam. They are generally inferior to central power plants due to lack of economies of scale hence higher unit cost of power. Successful adoption of wellhead powerplants for faster electrifications calls for state support and incentives in terms of subsidies, development of electricity grid, attractive feed in tariffs and tax incentives without which they won't compete favourably against the conventional central power plants. Generally, wellhead powerplants can make geothermal electricity projects more feasible with reduced barriers in investment and early electricity and revenue generation for investors. However, investment on temporary basis makes reasonable economic sense if the time between drilling the first productive well and completion of a central plant is more than one year. Incentives like high feed in tariffs and tax incentives may be necessary to make them competitive against the superior conventional powerplants.

9.2. Wellhead Generators

Wellhead powerplants are modular geothermal generating units that are factory designed and optimized for specific production well chemical and thermodynamic conditions and pre-assembled for specific site assembly[410]. According to [686], a geothermal power generating unit is “a modular miniature power plant installed close to the geothermal well pad.” With power produced being supplied to the national grid, regional grid, off grid applications and cogeneration within business entities like flower farming and salt extraction. Therefore, Wellhead power plants are small geothermal power plants usually installed at the geothermal production well pad. They generally vary from 100 kWe and 15 MWe in installed generating capacity[411, 687, 688]. These power plants do not need extensive steam field development except for connections between the well and the plant on site [416], and usually make use of steam from a specific production well [689]. The wellhead generators can also be installed on a production well being tested after drilling, and upon completion so that besides being used to generate test data and reports, they can generate electricity for field use on a temporary basis. This saves fuel needed to run diesel generators which are the main source of electricity for field development, mitigates pollution and can supply power to the local and public grid while project development is still underway [690]. Therefore geothermal wellhead generators put into useful application the idle wells between time of successful completion of production well drilling and completion of the central or conventional geothermal power plant, instead of

plugging off a productive well for many years and months awaiting completion of a central power plant [414].

Geothermal powerplants have several benefits compared to fossil fuel sources like supply of power with high load factor and availability but they also have challenges like high upfront costs, risks in resource development and limited availability of feasible resources [102]. Geothermal wellhead generators are small geothermal power plants with capacity generally between 0.1-15 MW that are installed at the well pad of a geothermal production well. Their design can be optimized to a specific well condition by avoiding interconnection of wells with steam at different pressure to a common separator which can render some low-pressure wells unproductive and those and unique high enthalpy will remain underutilized for the pressure far greater than the common separator pressure which is wasteful. Through wellhead power plants, the design operation pressure is specific to a specific well since wells even from the same steam field often have different thermodynamic, physical, and chemical properties. For example, if 3 wells one at 18, 15 and 6 bars are connected to a separator pressure of 10 bars, the well at a pressure of 6 bars won't contribute while the well at 18 bars will have underutilized capacity. To facilitate temporary application and relocation to new sites, wellhead generators can be made modular to allow for easy relocation to another well when needed.[226, 410, 687]

9.2.1. Technical Features of Wellhead Generators

The conventional geothermal power plants are generally large and therefore they enjoy economies of scale which leads to lower unit cost of electricity generation and higher efficiency, and better power plant performance indicators compared to the smaller power plants like the wellhead generators [81]. The main benefit of wellhead generators is probably their modularized design which increases their flexibility and facilitates quick project delivery at lower total costs compared to the large size central power plants. However the wellhead power plants have a challenge of inferior performance in terms of specific steam consumption, which is steam used to generate a unit power output, lower plant thermal efficiency and therefore higher cost of power to consumers as compared to power from larger central powerplants [411, 687].

9.2.2. Qualitative Differences Between Central and Wellhead Systems

There are significant differences between geothermal wellhead powerplants and the conventional or central power plants. These differences are summarized in Table 9-1.

Table 9-1: Conventional Versus Wellhead Power plants [411, 414, 416, 687, 690].

Parameters	Conventional Powerplants	Wellhead Powerplant
1 Set up period	The plant construction takes more than 2 years to complete and commission	The installation and commissioning generally take between 3-6 months
2 Customization	The plant design is not specific but well dependent.	Wellhead generators are designed for a specific production well conditions
3 Production wells needed	Central power plants receive steam from multiple wells	Often use steam from a single production well
4 Power plant capacity factor (CF)	The conventional powerplants enjoy higher capacity factor	The wellhead generators operate at a lower capacity factor compared to central powerplants
5 Unit cost of power	Central powerplants enjoy economies of scale hence enjoy lower unit costs	Wellhead powerplants have higher unit cost of power since they do not enjoy economies of scale
6 Electricity evacuation and transmission	Usually at high voltage to grid transmission system	Can be evacuated at lower voltage and connected to distribution grids
7 Non condensable gases	Specific well dependent	Specific well dependent

8	Power plant Flexibility and mobility	Central power plants are fixed and rigid in design	Wellhead generators are flexible and can be relocated to different sites
9	Generation specific steam consumption (SSC)	The central powerplants operate at a lower specific steam consumption hence have better steam economy	Wellhead powerplants have a higher specific steam consumption hence consume more steam for same output
10	Power plant availability	Higher availability factor	Lower plant availability

Table 9-1 shows that the main differences between power generation from wellhead generators and the central power plants on the project duration, number of wells, operational capacity factor, efficiency and generation and delivery voltage, specific steam consumption and plant flexibility. The common features include the emissions and the steam characteristics.

The most significant physical feature of wellhead generators in geothermal power generation is their modular construction in which the parts are assembled on a single skid at the manufacturing and assembly facility for assembly on a specific site or location. The wellhead powerplants are also simple in construction because they need fewer permanent civil works, having already been assembled in the factory prior to transportation for site installation [691]. This makes geothermal electricity development projects simple, cheap, and quicker to execute as it takes between 3 and 6 months to assemble and commission. Customization of wellhead units to specific production well conditions make it possible to optimize generation from a given production well hence with maximum power generation. Therefore, use of wellhead generators ultimately mitigates the limitations of traditional methods of geothermal electricity development like long gestation periods of up to 10 years, high risks and costs and waste of steam from low pressure wells and higher steam pressure wells in each steam field.

9.2.3. Design and Construction of Wellhead Generators

The main design features of a wellhead generator are demonstrated in Figure 9-1.

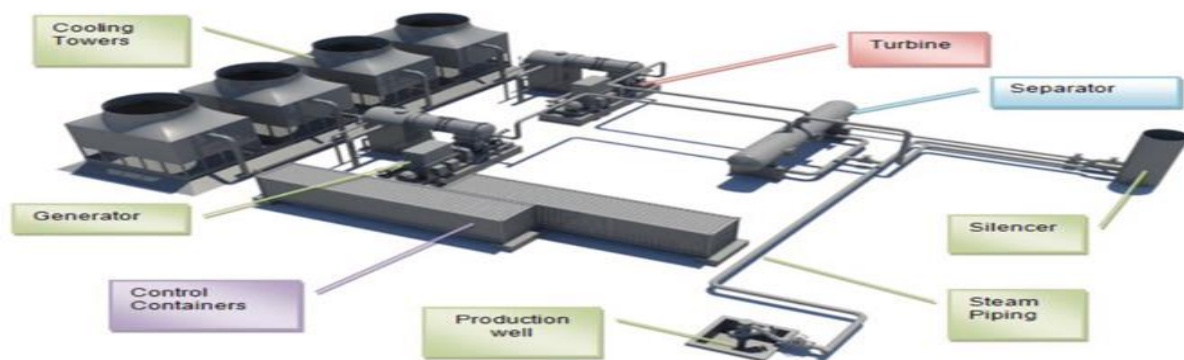


Figure 9-1: A Wellhead power plant

Figure 9-1 demonstrates the main features of a wellhead power plant which includes the separator, turbine, condenser, cooling towers, the control container as control room, silencer, generator, the production well and connecting steam piping. Figure 9-2 shows a photo of Olkaria geothermal wellhead plants in Kenya.



Figure 9-2: Photo of five Olkaria geothermal wellhead plants in Kenya[44, 58, 206, 347, 393, 394]

Figure 9-2 is a picture of showing five geothermal wellhead generators manufactured by GEG (Green Engineering Group Ltd.) on well pad WH-914, at Olkaria, near Naivasha in Kenya, with combined installed capacity of 27.8 MWe. The plants are assembled close to one another making it possible to have coordinated operation for all the units by the same staff.

For wellhead powerplants the generator is located just next to the well and therefore it requires very minimal piping. This reduces the impact from visual effect, cost of piping and steam transmission losses. The geothermal fluid the case of some wellhead plants like Eburru is

disposed of in open pits. Reinjection of the fluid means each well will have its own reinjection system or used fluid is collected from all or several plants and reinjected through a common well which makes reinjection system expensive to design and develop.

9.2.4. Elements of the Geothermal Wellhead Power Plant

A wellhead power plant design is a modular design with standard components. The plant may operate independently for each geothermal well or arranged in a power farm in a way that substitutes central power plants or mixed central and independent plants. The plant is generally supplied in 40 ft ISO containers to the site with standardized key components to enable quick installation and dismantling.

The layout is comprised of the following components:

The steam gathering system consists of wellhead assembly, pipes, valve, steam separator, brine disposal system, pressure regulation system, brine level control system, flash water collection and delivery system.

- i. A turbine with a generator unit, including their auxiliary devices.
- ii. Condensers, well pump, cooling towers, water circulation pump
- iii. An extraction system for non-condensable gases
- iv. Electrical systems for power evacuation including transformers.
- v. Instrumentation and control systems.

9.2.5. Characteristics and Benefits of Wellhead Plants

Wellhead power plants possess attractive characteristics and applications as electricity generation systems in the quest to increase the contribution of geothermal to the global electricity mix. These characteristics are as follows.

- i. They are easy to start compared with central powerplants and do not need auxiliary sources except for battery banks which are needed for instrumentation and control purposes.
- ii. They guarantee quick return on investment with less capital requirement making investment attractive.

- iii. They facilitate optimized geothermal resource use as they are designed to suit specific thermodynamic and chemical characteristics, hence maximum possible generation is possible from a production well.
- iv. With quick installation of factory preassemble units, wellhead power plants are a solution to the long wait to realize electricity and revenue from geothermal by quick delivery of power generating units even before the steam field is fully developed.
- v. With small plant sizes and phased development with low capital requirements, wellhead powerplants reduce the risks involved in geothermal electricity project execution.
- vi. With optimized generation, the cost per unit generation can be reduced through maximum generation from a geothermal well as opposed to centralized power generation which can render some wells unproductive while some are underutilized depending on the common separation pressure selected for central power generation.
- vii. Since field operations are often powered by diesel generators, wellhead powerplants can be used to substitute the diesel plants hence this reduces cost of fuel and environmental impact. As an example, the development of Menengai well 03 and 04 in Kenya spent US \$ 1.2 million in form of diesel power generation cost which was whopping 25% of the cost of the well drilling and development.
- viii. The development of wellhead powerplants offers flexibility that allows incorporation of other economic activities like combined heat and power to make better use of lower temperature brine or geothermal fluid.
- ix. Wellhead power plants have better powerplant performance indicators compared to the variable renewables like wind, solar and hydropower in terms of plant availability, capacity factor, reliability and in some cases, the unit cost of power[44, 58, 206, 347, 393, 394].

9.3. Sustainability of Geothermal Power plants

The future of geothermal energy will be influenced by the degree to which geothermal power plants are sustainably and economically deployed[692]. Geothermal electricity projects generally take a long time, and often encounter delays before completion and commissioning. The projects are also associated with economic, social, technical and environmental challenges[693]. Geothermal resource development is risky and requires huge financial resources and technical capacity[226]. It is therefore necessary to do a careful feasibility

study that covers technical, environmental, electricity demand, financial/economic, legal, and socio-economic aspects[407, 693].

9.4. Environmental Impact of Wellhead Power Plants

The operation of wellhead powerplants encounters several notable challenges. These challenges include plant trips during operation which cause steam blowing, noise and depositing of brine on nearby farms. Non-condensable like hydrogen sulfide and carbon dioxide gases present a significant environmental challenge except for organic Rankine technology where they remain confined in the working fluid loop and re-injected through the injection well. To control the non-condensable gases, a gas extraction system should install. In the environmental impact of Eburru wellhead power plant in Kenya, it was established that the local community has been impacted negatively with high levels of hydrogen sulfide, higher ambient noise levels, high boron concentrations and other negative environmental impacts. These effects are discussed below.

- i. The chemistry of brine effluent exceeds recommended requirements for effluent discharge to the environment in terms of total dissolved solids, pH, electrical conductivity, chlorides, Boron, and Barium.
- ii. The hydrogen sulfide in the atmosphere away from the power plant exceeded the tolerant limits of 0.0355 ppm as far a 100 m in the northern direction of the power plant.
- iii. The ambient noise levels exceeded tolerable limits of 35 dB [A] as far as 1100 m from the power station although the level is not too high to cause hearing impairment.
- iv. The commissioning of Eburru wellhead power plant brought conflicts between the local community and the power plant owner/operator. Notable environmental issues include crop damage due to venting of geothermal fluids resulting from several trips of the plant.
- v. Between July 2014 and December 2015, Eburru wellhead plant realized 383 trips which led to venting of the plant with serious environmental implications.
- vi. Heat or thermal pollution in form of hot geothermal fluid is a common scenario whenever the geothermal fluid is not reinjected back to the steam field. This hot water causes damage to flora and fauna and can also cause accidents if not well secured.

- vii. In Philippines, it was observed that atmospheric venting of production wells produced brine spray that defoliated up to 100 m of dense forest from the geothermal production well.

9.5. Social Impact of Geothermal Electricity Projects

Generally, investment in geothermal energy projects adds societal value in terms of direct and indirect employment. However, geothermal energy related activities in general offer less jobs than the traditional energy sectors of the economy]. All electricity generation projects are to some degree associated with conflicts between the community, investors, and project developers. Investors in wellhead geothermal plants should engage the local community as early as possible for the project to be executed with minimal resistance. Experience by Kenya Electricity Generating Company PLC. (KenGen) demonstrates the need for an inclusive environment and social impact assessment. This is necessary to facilitate early engagement of the community, which yields better results and should therefore be encouraged for all projects.

The socio economic impacts of both central and wellhead power plants based on studies carried out at Olkaria geothermal fields;

- i. The locals benefit using facilities developed by the geothermal electricity companies like water supply, shops, and schools.
- ii. Very few of the locals are employed mainly in casual and manual jobs like security guards, messengers, cleaners, laborers, and contracted services like carpentry.
- iii. Fear of the effect of increasing dust levels and repugnant smell the project could bring if it expands towards their homesteads.
- iv. Increasing cases of respiratory diseases especially asthma, eye problems, colds, and flu's which locals attribute to the emissions from the geothermal power plants
- v. The Maasai community who resided in the vicinity of the power plants claimed that they were displaced/resettled from their homes without compensation as they were simply told to move from the project sites.
- vi. Reduction in land size(s) as the project expands which negatively affects their main economic activity which is rearing cattle and other livestock as grassing land is taken away.

- vii. Geothermal projects led to a reduction in family size due to the gradual reduction in community land which affects their cultural heritage.
- viii. The local community complains about incidents of miscarriages and children being born with deformities or retarded. They attribute this to the existence of geothermal electricity activities.
- ix. The local community complains of foreign cultural attitudes penetrating their culture and causing cultural conflicts because of interaction with outsiders.
- x. Unsustainable exploitation of geothermal resources can lead to the reduction of water levels and eventual drying of natural water springs, wells and rivers which provide fresh water to local communities and wildlife.
- xi. The local communities like the Maasai have limited access to electricity and rely on firewood as the source of energy even when they live next to the geothermal power stations.
- xii. Extensive pipelines which are a major feature with traditional geothermal power plants and less with wellhead power plants can interfere with the migratory paths of wild animals hence negatively impact on natural habitat as most of these geothermal resources in Kenya and Japan and many other countries are in protected natural habitats like game parks[44, 58, 388].

9.6. Wellhead Versus Conventional Power Plants

The differences between wellhead and the conventional geothermal power plants are presented in Table 9-2.

Table 9-2: Conventional Versus Wellhead Power plants [44, 58]

	Parameters	Conventional powerplants	Wellhead powerplant
1	Set up period	The plant construction takes more than 2 years to complete and commission	The installation and commissioning generally take between 3 and 6 months
2	Customization	The plant design is not specific well dependent.	Wellhead generators are designed for a specific production well conditions

3	Production wells needed	Central power plants receive steam from multiple wells	Often use steam from a single production well
4	Power plant capacity factor (CF)	The conventional powerplants enjoy higher capacity factor	The wellhead generators operate at a lower capacity factor compared to central powerplants
5	Unit cost of power	Central powerplants enjoy economies of scale hence enjoy lower unit costs	Wellhead powerplants have higher unit cost of power since they do not enjoy economies of scale
6	Electricity evacuation and transmission	Usually at high voltage to grid transmission system	Can be evacuated at lower voltage and connected to distribution grids
7	Non condensable gases	Specific well dependent	Specific well dependent
8	Power plant Flexibility and mobility	Central power plants are fixed and rigid in design	Wellhead generators are flexible and can be relocated to different sites
9	Generation specific steam consumption (SSC)	The central powerplants operate at a lower specific steam consumption hence have better steam economy	Wellhead powerplants have a higher specific steam consumption hence consume more steam for same output
10	Power plant availability	Higher availability factor	Lower plant availability

From Table 9-2, it is observed that the main differences between power generation from wellhead generators and the central power plants are on the project duration, number of wells, operational capacity factor, efficiency and generation and delivery voltage, specific steam

consumption and plant flexibility. The common features include the emissions and the steam characteristics.

9.7. Results and Discussion

Although geothermal energy has a huge potential for power generation, it currently contributes less than 1% of global electricity generation capacity. The generation capacity grew from 8.7 GWe in 2005 to 15.61 GWe in 2020, representing an average annual growth of 4.01%. Wellhead and central geothermal powerplants can adopt various conversion technologies that are common to both although to different sizes. The main reason why geothermal generation growth is low and hence limited contribution is that it takes a very long time between the time the first viable resource is established and the time to construct and operate a central powerplant which exerts financial pressure to financiers and developers. It is this challenge that wellhead generators can be used to address by putting to immediate use the wells that have been drilled and tested. The main difference between wellhead power plants and the conventional powerplants is that wellhead power plants often use steam from one or in some cases few closely located geothermal production wells with limited steam pipeline connections and steam field development.

Technically, the central power plants enjoy economies of scale compared to wellhead powerplants and therefore are superior to wellhead powerplants in many powerplant performance indicators which include capacity factor, availability, load factor, unit cost of power generation, among others. On the other hand, the wellhead power plants possess unique and desirable characteristics like quick project delivery and short lead times, optimal use of specific geothermal wellhead thermodynamic conditions like temperature, pressure, and brine characteristics for maximum power generation by optimization of flash pressure and temperature as well as well flow characteristics which influence the installed capacity and technology selection as opposed to central powerplants whose design and operation is guided by average parameters of the entire steam field and all connected wells. Selection of the flash pressure often leads to underutilization of high enthalpy wells and even cutting out of low enthalpy and low-pressure wells. Both wellhead and conventional power plants. Selection of conversion technology should balance between efficiency, exergy, and cost optimization to ensure optimum geothermal resource exploitation. The available geothermal energy to

electricity conversion technologies includes dry steam, flash steam, binary, combined and hybrid conversion technologies. The factors considered in technology selection are efficiency, financial and economic factors and geothermal resource and reservoir characteristics.

Some desirable economic features of wellhead generators include reusability hence savings on initial cost, lower investment capital requirements, flexibility and portability of generators, and faster electricity generation capability. There is a need to carry out detailed socioeconomic studies to establish economic viability of wellhead power plants ahead of implementation to guarantee viability. Overall, wellhead powerplants have significant economic and financial impact in terms of early revenue for investors, early electricity for steam field development, hence savings on conventional energy since diesel powerplants are often used to power rigs and other field operations that need electricity. Jobs created and power generated in the early stages of the projects in temporary application as well as including aft multiplier effect to rural economies, less financial risks, early return on investment permanent applications enhances decentralized generation while boosting rural economies with stable electricity and revenue to local authorities and communities. This further adds value and makes investment in geothermal electricity more competitive and viable and hence attractive to investors and financiers. However, investment in wellhead generators make economic sense when the time difference between the instant the wellheads start generating and the time the traditional powerplants start generating is more than one year but required adequate economic evaluation ahead of investment.

On the environment, geothermal energy exploitation does not cause serious negative impacts to the environment compared to fossil fuel. The main challenge with most wellhead generators is lack of used fluid injection well hence the challenge of disposal causing brine related pollution. This also hampers the sustainability of resource use as lack of reinjection limits the replenishment of the geothermal resource in the reservoir. Therefore, geothermal fluid reinjection should be considered as a necessary measure for sustainable geothermal resource use especially where the wellhead power plants are installed on permanent basis for sustainability purpose even though it will increase the installation cost. Common environmental issues from operating wellhead powerplants include noise pollution and steam blowing especially during plant trips and brine pollution where reinjection is not practiced. Participatory techniques should be applied to mobilize the local community and resources to

guarantee social sustainability of the wellhead powerplant projects. Participatory research can be used to generate facts on effects of geothermal on the environment and hence develop mitigation strategies. These strategies and measures can enhance project acceptance and increase the social value of wellhead power generation.

Despite the limitations highlighted, wellhead power generation promise to be a viable solution to the many challenges facing geothermal electricity generation namely high risks and slow rate of project development due to long delivery times and huge capital requirements for conventional or central geothermal powerplants. The wellhead power plants should be incorporated in geothermal electricity generation projects both for temporary and permanent application. Generally, wellhead powerplants can make geothermal electricity projects more feasible with reduced barriers in investment and the commercial operation data.

9.8. Conclusion

Geothermal energy has a significant role to play in the global transition to renewable and low-carbon energy systems because of its ability to supply steady and flexible electricity particularly for baseload demand because of its cost competitiveness with fossil fuel energy options. However, geothermal faces a challenge of long project development times with conventional power plants taking average of 5–10 years and with high risks associated with drilling and unproductive wells which discourage private investment and quick deployment. As the world community works hard to implement the Paris Agreement on limiting greenhouse gas emissions and the related consequences of global warming, geothermal energy has proved to be a reliable energy source for electricity grid generation producing power with excellent capacity factor of over 95%. However geothermal electricity currently accounts for less than 1% of global electricity generation due to low growth in generation capacity of about 4.01% annually between the year 2005 and 2020, mainly due to huge capital requirements, high upfront development risks and long project delivery period of 5–10 years.

The use of wellhead generators will deliver electricity within 3–6 months of well drilling and testing, hence guaranteeing early return on investment and supply of green electricity. Although wellhead generators are inferior to central power plants in terms of performance indicators like capacity factor, availability factor and specific steam consumption, their use

will significantly reduce project risk, early faster delivery of electricity and low capital requirements with optimum specific geothermal well resource utilization.

Wellhead technology involves using steam from geothermal wells that have been drilled, are productive but remain idle awaiting the development of a conventional geothermal steam power plant to generate electricity. In some cases, wellheads are built on permanent basis on isolated geothermal wells. This enables the investor to enjoy early electricity and revenue streams before completion of a power plant and continues generation from single or few productions well. The wellhead technology puts into use the idle geothermal resource between time of successful completion of the steam well drilling and completion of the central or conventional geothermal power plant. In wellhead electricity generation, steam from a geothermal well is converted to electricity in a wellhead power plant unit that is installed just above or close to the drilled geothermal well. The plant has no steam field development except for brine and cooling tower blow down disposal systems developed for the well head plant.

9.9. Recommendations

This study has demonstrated the significant potential of wellhead power plants in the faster and economical realization of geothermal electricity either as temporary, permanent, or mixed wellhead and central power plants. Policy recommendations suggested including the need to give serious consideration for brine reinjection for geothermal powerplants. Policy incentives include tax holidays and reliefs for wellhead plant equipment and attractive electricity feed in tariffs.

CHAPTER 10:

WASTE TO ENERGY PATHWAYS

10. Overview

This chapter presents various waste to energy pathways extracted from the authors publications referenced as [33, 57, 82, 100, 360, 387, 393] . The feasible waste to energy options include waste to energy through anaerobic digestion which produces biogas, solid municipal waste to energy through combustion, slaughterhouse waste to biogas and electricity as well as bagasse to heat and power in sugar factories.

10.1. Introduction

Energy recovery from waste or Waste-to-Energy (WtE) is an effective attractive value addition and waste management option for many countries. Various WtE technologies offer valuable energy, reduce the burden on the land in form of landfill disposal and mitigate greenhouse gas emissions by avoiding decomposition and substitution of fossil fuel generated power. Because of these benefits, the global market for WtE technologies has experienced substantial growth with now over 1200 operating plants across 40 countries. The Waste-to-energy power plants burn municipal solid waste (MSW) to generate steam in a boiler that is used to run a Rankine cycle steam turbine to generate.

10.1. Municipal Solid Waste to Energy Pathways

This section contains work published in paper [360] on conversion of municipal solid waste to electricity through combustion. Most urbanized areas, the common source of trash for waste-to-energy use is derived from municipal waste, i.e. the trash that we all accumulate daily and can't be recycled or composted in a process called municipal waste treatment, or MWT. Incineration is traditionally, the most used method for waste-to-energy (WtE) conversion but we have lots of up-and-coming, progressive waste-to-energy solutions.

Municipal Solid Waste is a mixture of energy-rich materials like paper, plastics, yard waste, and products made from wood as well as noncombustible materials. Solid waste is the useless, unwanted products in the solid state derived from various activities of and discarded by society. Waste is generated continuously in every single way from our daily activities. Urbanization is associated with high population density, increased waste generation, and

increased littering, increased pressure on limited and diminishing free land for disposal and environmental challenges. Municipal solid waste is the non-hazardous part of solid wastes generated by businesses, households except for industrial processes waste, building debris, construction wastes, offal, sludge. Municipal solid waste (MSW) also called trash or garbage includes tires, furniture wastes, newspapers, plastics, containers, packaging materials. For every 100 kg of MSW in the United States, about 85 kg can be burned as fuel to generate electricity. The Waste-to-energy power reduce can reduce 2,000 kg of MSW to ash weighing about 300 kg to 600 kg, while the volume of MSW can be reduced about 87%.

The world urban population grew to reach 50% of the global population in 2015 and is expected to reach 70% of the world population by the year 2050 with developing countries accounting for most of this growth. Africa's urban population is expected to grow from 470 million in 2015 to 1.2 billion by 2050. This is expected to come along with significant challenges of municipal solid waste (MENR, 2017). The rate of growth of solid waste will outpace the rate of urbanization according to the projections of the World Bank. It is projected that municipal solid waste was to grow from 0.64 kg/person per day in 2002 to 1.2 kg/person per day in 2012 or 1.3 billion tons per year, and 1.42 kg per person per day or 2.2 billion tons by the year 2025.

The aim of this research was to reduce the environmental impact of municipal solid waste through the development of a waste to electricity Rankine cycle power plant to generate steam and electricity from municipal solid waste in Nairobi city as a solution to waste management challenges. The electricity generated will lead to avoided generation from fossil fuel sources which are polluting and contribute heavily to greenhouse gas emission from power generation.

10.1.1.Municipal Solid Fuel as Fuel for Power Generation

The heterogeneous nature of composition of MSW makes it difficult for traditional technologies of fuel combustion and processing. Presence of garbage in municipal solid waste reduces its calorific value to as low as 800 kca/kg. If the waste is processed, a study on Indian MSW showed that the energy content will vary from 3000-4000 kJ/Kg which is comparable to Indian coal (Muthuraman & Reddy, 2013). In another study on characteristics of refused-derived fuel (RDF), it was established that Gross calorific values (GCVs) varied between 14.6 and 40.2KJ/g. The calorific value significantly increases when the composition of plastics is

high, presenting 33.6 ± 0.5 , 40.2 ± 1.0 , and 28.6 ± 0.4 for non-packaging hard plastics, packaging foils, and packaging polyethylene terephthalate (PET), respectively. Total chlorine contents are less than 4 mg/g, except for non-packaging hard plastics. Cadmium contents of organic kitchen waste (KW) and non-packaging hard plastics (HP) respectively are below the detection limit and the lead content of kitchen waste is also below it. These results show that MSW can be used as refused derived fuel and conversion can be done through various conversion technologies.

10.1.2.Composition of Nairobi’s MSW.

In the analysis of MSW as a fuel in waste to energy conversion, important parameters are the moisture content, composition, density calorific value. Bulk density influences costs involved in collection, storage, and tipping. The bulk density in most developing countries varies from 120 kg/m^3 to 540 kg/m^3 while calorific value generally varies between 1.578 MJ/kg to 20 MJ/kg based on studies carried out in Ghana, Senegal, and Malaysia. A study on composition of waste in Nairobi city gave the results presented in Table 10-1.

Table 10-1: Composition of MSW in Nairobi

MSW Constituent	Composition
Plastics	14.15
Organic or food waste (Putrescibles)	59.33
Inorganics (bottles, metals, and others	7.74
Leather & Textiles (LT)	7.53
papers	12.65
Total	100%

Table 10-1 shows that organic waste constitutes the largest portion of MSW in Nairobi with about 59.33% while leather and plastics are on the least. The composition of municipal solid waste varies over time and place. For Nairobi, the composition between 1985 and 2010 is

presented in Table 10-2

Table 10-2: The Nairobi waste compositions, 1985 – 2010

Constituent	Composition
Plastics	13.8%,
Organic or food waste (Putrescible)	58.8%
Inorganics (bottles, metals, and others)	8.30%
Leather & Textiles (LT)	7.80%.
papers	11.30%,
Total	100%

Table 10-2 shows that organic or food waste constitute the highest composition in municipal solid waste while leather and textile is the least component of the Nairobi's MS. Figure 10-1**Error! Reference source not found.** shows the composition of domestic municipal solid waste.

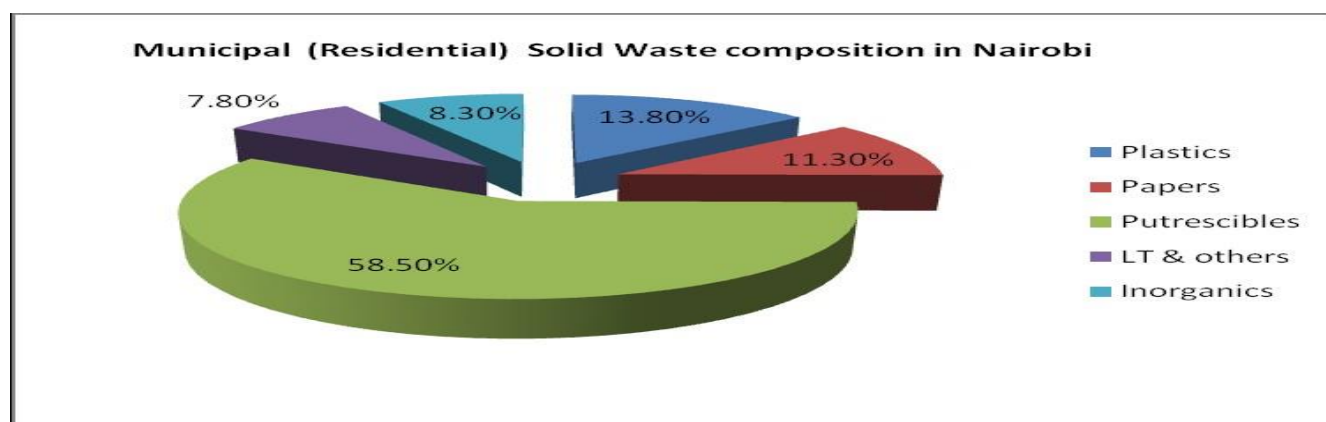


Figure 10-1: Composition of the MSW f 1995 and 2010.

From Figure 10-1 it is noted that putrescible or food waste are the main constituent of domestic solid waste is Nairobi. Other materials are plastics, paper, leather & textiles, and inorganics.

10.1.3. Physical and Thermodynamic Properties of Nairobi's MSW.

The moisture content of MSW significantly affects its combustion characteristics and the heat value. The contents vary with type of waste and the season or weather. The moisture content of the MSW in Nairobi varied from a low of 63.2% and a high of 75.0% giving a weighted average of 68.9% as moisture content.

The mass density of the MSW in Nairobi varies from 296 kg/M³ to 282 kg/m³ and average of 289 kg/m³. These compares unfavorably with the 410 to 546 kg/m³ sampled in Ghana, but more favorable and less varied compared to 120-330 kg/m³ sampled in Kuala Lumpur. It should however be noted that the properties tend to vary from time to time based on people's consumption trends and items consumed.

The mean calorific value of MSW for Nairobi is estimated at a low of 12.36 MJ/kg and a high of 18.36 MJ/kg and average of 15.70 MJ/kg for the dominant organic components and average of 12.48 MJ/kg. This compares unfavorably with the mean calorific value of coal taken as 23.25 MJ/kg hence we expect less power out per unit mass from the MSW in Nairobi city.

10.1.4. Overview of the MSW Power Plant

MSW is usually burnt at special waste-to-energy plants that use the heat from the flue gases generate steam for generating electricity by running a steam turbine with potential for process heat application. In 2018, 68 U.S. power plants generating 14 billion kWhrs of electricity burnt 29.5 million tons of combustible MSW. Biomass materials content accounted for 64% of the weight of burnt MSW and about 51% of this electricity produced with the remainder being non biomass sources, mainly plastics. Many large landfills also generate electricity by using the methane gas by decomposing biomass in landfills.

Burning waste generates steam, hot water and electricity and reduces the amount of material that would probably be buried in landfills by about 87% by volume. During thermal treatment the energy content is released, and the volume and weight of waste reduced by approximately 90%. Generally, a MSW cogeneration plant operates 90%-95% of the time with 5% taking care scheduled/planned maintenance and unplanned events also called forced plant outage. Figure 10-2 illustrates a typical mass burn waste to electricity power plant.

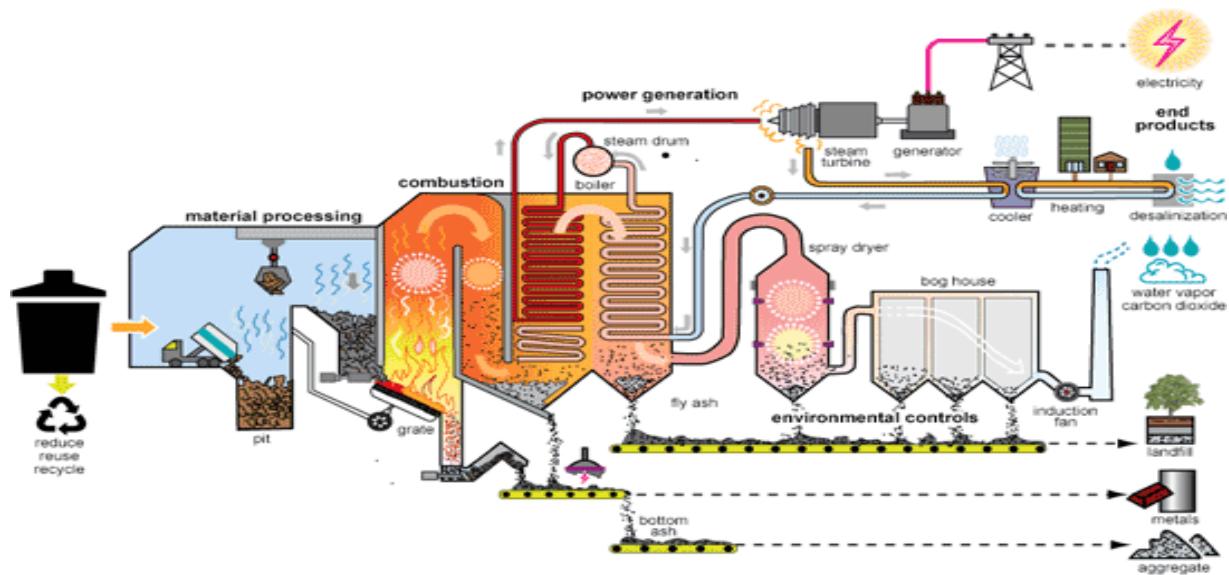


Figure 10-2: Model of solid waste cogeneration plant.

From Figure 10-2, it is noted that the main elements of a MSW power plant are the tipping feed chute, moving grate boiler, electrostatic precipitator, the stack, fans, turbine other elements. The first step shows that before the incineration in mass boiler, the waste should be subjected to reduce, reuse and recycle options of solid waste management. The process of generating electricity in a mass-burn waste-to-energy plant has seven stages:

- i. Waste is dumped from garbage trucks into a large pit for temporary storage and preparation.
- ii. The MSW is grabbed and dumped in a combustion chamber.
- iii. The MSW is burned, releasing heat and flue gases which are transmitted by means of a draught to the chimney/stack with heat exchangers installed along the path.
- iv. The heat is transferred from the flue gases to water and converted to into steam in a boiler.
- v. The generated steam which is at high-pressure and temperature as well as dry is piped to Rankine cycle steam turbines steam turns the blades of a turbine generator to produce electricity.
- vi. An exhaust cleaning system removes pollutants from the combustion gas before it is

released through a smokestack to the environment.

- vii. Ash deposits are collected from the boiler and the air pollution control system for disposal.

10.1.5.Availability of Municipal Solid Waste (MSW).

Table 10-3**Error! Reference source not found.** and Table 10-4 demonstrated the waste fractions and the projected waste generation from the year 2009 to 2019 taking population into perspective.

Table 10-3: Technical Data Obtained.

Waste fractions	2009	2010
Organic waste	1671	2160.3
Paper	574.5	484.7
Plastic	528.6	377.4
Glass	65.66	51.9
Metal	65.66	24.2
Others	374.3	363.5
Total Waste	3283 tons	3462 tons

From Table 10-3, it is noted that the total municipal solid waste for 2010 was 3,462 tons. However, some elements like metal and glass may be of no value in combustion for steam generation and can be removed. There is a significant increase in the total amount of municipal solid waste produced and this could be attributed to population growth and an increase in affluence. The amount of plastic and paper waste is seen to have decreased and this is due to efforts in recycling and reusing the materials. The ban on plastic bags by NEMA will see a further decline in the number of plastic wastes. Table 10-4 illustrates the real and

projected MSW for Nairobi.

Table 10-4: Projection of Solid Waste Generation

Projected population		
Year	Logistic Population (millions)	Total MSW (tons/day)
2009	3.5633	3283
2010	3.7046	3462
2011	3.8475	3644
2012	3.9918	3829
2013	4.1372	4016
2014	4.2833	4206
2015	4.4299	4398
2016	4.5766	4592
2017	4.7231	4788
2018	4.8692	4986
2019	5.0145	5186

From Table 10-4, it is noted that the total MSW for Nairobi increased from 3283 tons in 2009 to 5186 tons in 2019.

From Table 10-5 it is deduced that most of the heat recovery from flue gases to water/steam takes place in the evaporator of the steam generator, followed by the economizer and super heater.

10.1.6. Technical Specifications of Proposed MSW Powerplant for Nairobi City

Based on the design analysis resented in[360], the technical specifications for the proposed MSW power plant are summarized in below.

Table 10-5: Summary of the proposed power plant cycle (authors' calculations)

Parameter	Value	Parameter	Value
Surface Condenser		Cooling Tower	
Cooling water outlet temperature T_{co} ($^{\circ}\text{C}$)	38	Inlet temperature of the water T_1 ($^{\circ}\text{C}$)	38
Cooling water inlet temperature T_{ci} ($^{\circ}\text{C}$)	26	Outlet temperature of the water T_2 ($^{\circ}\text{C}$)	26
Steam inlet. temperature T_{si} ($^{\circ}\text{C}$)	99.6	Dry bulb temperature T_{db} ($^{\circ}\text{C}$)	30
Steam outlet. temperature T_{so} ($^{\circ}\text{C}$)	29.0	Wet bulb temperature T_{wb} ($^{\circ}\text{C}$)	22
Mass flow rate of steam $\dot{m}_c$ (Kg/s)	20.72 33	Inlet air temperature T_{a1} ($^{\circ}\text{C}$)	20
Velocity of cooling water per tubes w (m/s)	2.896	Make up water mass flow rate (kg/s)	18.247 9Kg/s
Steam Turbine		Thermal Efficiency	
Main steam conditions	15bar	Energy addition	53.922 2MW
Output (MW)	11.78 53	Energy Rejection	50.944 MW

Inlet steam temperature	350°C	Efficiency	21.15 %

From Table 10-5, it is noted that the proposed MSW mass burn power plant will have steam flow rate of 20.7233 kg/sec at 15 bars at 350°C and turbine power output is about 11.79 MW.

10.1.7.Conclusion

This study showed that the city of Nairobi faces significant challenges with its municipal solid waste (MSW) management leading to large wastes remaining uncollected, environmental hazards and lack of space at Dandora dumping cite thereby making MSW a health hazard. The proposed powerplant can process 3000 tons of municipal solid waste per day and generate 12 MW of electricity. Consistent processing of solid waste by the plant will consume about 1,008,000 tons per annum, thereby reducing about 34% of the total waste that goes into the Dandora dumpsite. By streamlining of waste collection services in the city, an extra generation line can be installed to process 6000 tons of waste per day bringing the annual reduction of waste in Dandora to about 64%. The electricity produced from the plant will be connected to the national grid increasing the number of households connected to electricity and avoid generation from fossil fuels thus preserving the environment. Implementation of this project can provide an environmentally friendly and sustainable solution for the disposal of municipal solid waste for the city of Nairobi. It will also generate revenue from electricity sales which will boost the solid waste management system and create extra income for the county government of Nairobi.

10.1.8.Recommendations

The following recommendations are suggested to enhance electricity generation from municipal waste.

- i. Cities and governments should partner with the private sector to access technology and capital for investment in waste to electricity projects. These id because of lack of own capacity to develop capital projects of this magnitude.
- ii. Cities and municipalities should streamline their MSW systems to ensure that all waste is collected and managed to ensure clean, healthy cities.

- iii. Policy measures should be put in place to encourage cities to invest in commercial waste to electricity projects through attractive feed in tariffs and tax incentives.
- iv. The correct size of the power plant should address current and future generation of municipal solid waste.

10.2. Anaerobic Digestion for Biogas Production and Applications an Energy Resource

10.2.1.Overview

The contents of this section is published in references [28, 34, 62, 389] as journal papers, conference, and book chapter on biogas energy resource authored by the candidate. The studies showed that biogas is competitive, viable and generally sustainable energy resource due to abundant supply of cheap feedstocks and availability of a wide range of biogas applications in heating, power generation, fuel, and raw material for further processing and production of sustainable chemicals including hydrogen and carbon dioxide and biofuels. The capacity of biogas power has been growing rapidly for the past decade with global biogas generation capacity increasing from 65 GW in 2010 to 120 GW in 2019 representing a 90% growth. This study presents the pathways for use of biogas in the energy transition for power generation and production of fuels. Diesel engines, petrol or gasoline engines, turbines, microturbines, and Stirling engines offer feasible options for biogas to electricity production. Biogas fuel can be used in both spark ignition (petrol) and compression ignition engines (diesel) with varying degrees of modifications on conventional diesel engines and petrol engines. In internal combustion engines, the dual fuel mode can be used with little no modification compared to full engine conversion to gas engines which may require major modifications. Biogas can also be use in fuel cells for direct conversion to electricity and a raw material for hydrogen and transport fuel production which is a significant pathway to sustainable energy development. Enriched biogas or biomethane can be containerized or injected to gas supply mains for use as a renewable natural gas. Biogas can be used directly for cooking, and lighting as well as for power generation, but can also be used for production of other fuels and Fischer-Tropsch (FT) fuels. Upgraded biogas/biomethane which can also be used to process methanol fuel. Compressed biogas (CBG) and liquid biogas (LBG)

can reversibly made from biomethane for various direct and indirect application as fuels and power generation. Biogas can be used in processes like combined heat and power generation from biogas (CHP), compression to bio-CNG and bio-LPG for cleaned biogas/biomethane. Fuels are manufactured from biogas by cleaning, and purification before reforming to syngas, and partial oxidation to produce methanol which can be used to make gasoline. Syngas is used in production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process.

10.2.2.Biogas Production Process

Different types of organic matter can be digested anaerobically to produce biogas. The final step in the chain of chemical and biological processes used to break down organic matter for the purposes of producing biogas and managing garbage is called anaerobic digestion[694]. The production of biogas involves the controlled breakdown of organic material into smaller molecules by several anaerobic bacteria [694, 695]. Chemical reactions such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis occur during anaerobic digestion, which produces biogas from biomass [694, 696].

Biogas is produced by the microbial action in the digester soon after biomass is prepared and fed after undergoing preparation and a gradual fermentation process, the biomass is introduced into the reactor, where microbial activity within the digester rapidly generates biogas. Consequently, the process is a consequence of bacterial consumption of organic matter, specifically proteins, carbohydrates, and lipids/fats. This microbial digestion gives rise to the production of gases, predominantly methane and carbon dioxide. The process of biogas production encompasses several distinct stages, namely pretreatment, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Prior to introducing feedstock into the digester for the purpose of anaerobic degradation, the initial stage of biogas production involves feedstock processing or pretreatment. The pretreatment of feedstock is an essential and pivotal stage to mitigate instances of failure, enhance the production and enhance the quality of digestate, among other advantageous outcomes.

10.2.3.Methodology

This research involved review of published peer reviewed papers and official reports on sources of biogas, its production processes, and applications. The literature used was

published between 1932 and 2022 to give a clear view of the past and status of biogas technology and applications. The sustainability dimensions of biogas energy were covered including social, institutional, technical, economic, and environmental at local and international levels. A review of policies and regulations on national and international levels is presented. Based on literature and the requirements of sustainable energy transformation, the role of biogas is clearly defined now and in future. Biogas feedstocks, feed preparation, conditions for optimal production and composition of both biogas and biomethane are presented. Additionally, biogas upgrading technologies are also presented including quality and process sustainability. Finally current and future applications of biogas are also presented as a sustainable energy option in the energy transition.

10.2.4. Anaerobic Digestion Process

The bio digestion process for biogas production involves several key stages, namely the pretreatment stage of raw materials, anaerobic digestion (AD), purification of raw biogas, final biogas utilization, and posttreatment of digestate. Impurities like sand are, stones, plastics etc. removed from the feedstock at the pretreatment stage, and the total solids (TS) concentration and temperature of the feedstock moderated for optimum bio-digestion[697]. The digester constitutes the core or the main element of the biogas production plant whose size and performance characteristics should be selected based on specific process and output conditions. At the terminal stage of the biogas production, the residue and slurry are further treated for intended application e.g. biofertilizer[34, 296, 328]. The process flowchart of a biogas plant process is shown in Figure 10-3.

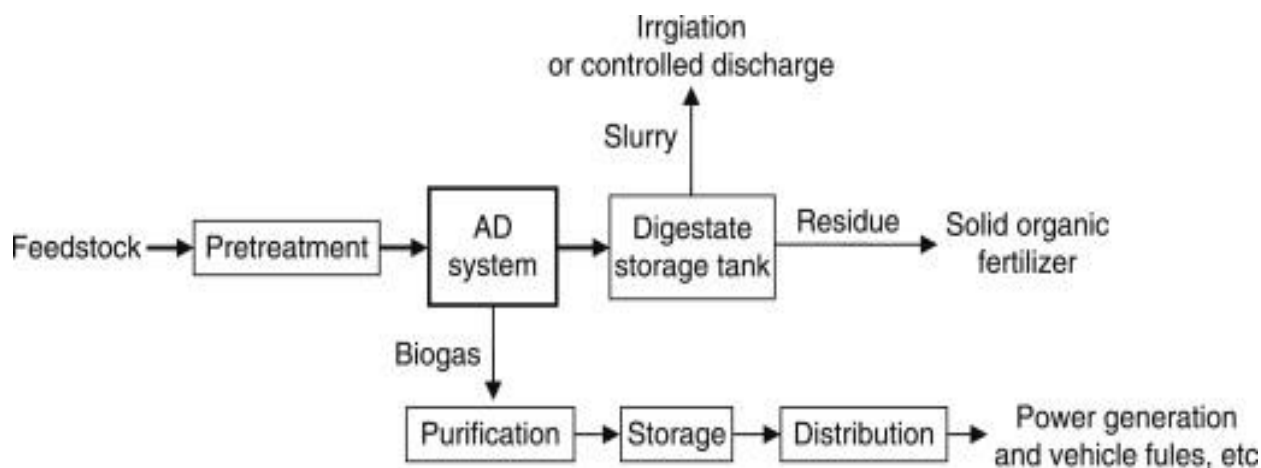


Figure 10-3: Biogas plant operation process and products[62, 697]

From Figure 10-3, it is noted that the process of biogas production starts with feedstock collection and pretreatment before it is fed into the anaerobic digester. The main products of the anaerobic digestion process are raw biogas and digestate. Biogas can be purified and stored ready for distribution and consumption. The digestate in slurry form is prepared or conditioned and applied in irrigation or controlled discharge as an organic fertilizer. Digested can also be used as a solid fertilizer in addition to slurry form. The various stages of biogas production are discussed as follows.

10.2.4.1. Pretreatment Stage

Pretreatment is implemented as a strategy to enhance the breakdown of substrates, thereby enhancing the overall efficacy of the process. The employed pretreatment methods can be classified into four primary categories: chemical, mechanical, thermal, and enzymatic processes. The aforementioned techniques are designed to expedite the process of decomposition, although it is crucial to acknowledge that they do not necessarily lead to augmented biogas generation[698]. First, the feedstock is washed, then it is macerated, screened, and finally pressed (however these stages can change depending on the feedstock). Mechanical parts can survive longer if they are free of contaminants like plastic, and magnetic traps are used to effectively eliminate magnetic pollutants. Glass, eggshells, pottery, bones, and sand are among nonmetallic impurities that must be removed during the preparation step. These pollutants do not decompose during digestion and hence accumulate as deposits at the digester's base[699].

Enzymes are required for hydrolyzing lignocellulose, which is necessary for digestion. An economic and technical barrier to producing biogas from lignocellulosic waste is its complicated structure. Strong and compact molecular bonds are formed in lignocellulose due to the presence of cellulose, hemicellulose, and lignin. The effectiveness of pretreatment is critical for maximizing lignocellulose's potential as a biogas source. Pretreatment, in general, hastens reactions, boosts biogas yields, and creates a plethora of novel substrates[59, 698].

Technological advancements in pretreatment have enhanced biogas yields from lignocellulosic feedstocks, resulting in lower methane emissions into the atmosphere. Pretreatment is crucial because it increases biomass digestion and provides more biogas than without it by facilitating microbial breakdown of lignocellulose and its polymers, especially cellulose and hemicellulose.

It has been shown that autoclaving and microwave heating can cause the hydrolysis of several non-biodegradable chemicals found in municipal garbage. Biomass pretreatment achieves this by partially or completely breaking down the feedstock to yield fermentable sugars, reducing the lignin barrier, and smoothing out the crystalline structure of cellulose [275, 386, 387, 698].

Table 10-6: Pretreatment methods and applications [698]

	Technology	Merits	Demerits
1	Feedstock milling	▪ Does not produce any process inhibitors. ▪ Increased methane (5%–25%)	▪ High energy requirements ▪ High maintenance cost
2	Feedstock Extrusion	▪ Extrusion increases the surface area to volume ratio	▪ Leads to increase energy consumption. ▪ Increases equipment maintenance cost
3	Steam pretreatment/ steam explosion	▪ Increased cellulose fiber reactivity. ▪ Can make use of process energy/biogas	▪ Risk of producing inhibitors (e.g., furfural and HMF) ▪ Reduces digestible biomass due to lignin condensation. ▪ More process energy input and reduced net energy output. ▪ Precipitation phenomena

4	Hot water treatment	▪ Solubilized hemicellulose and lignin products are present in lower concentrations. ▪ Reduced risk of producing inhibitors like furfural and HMF) ▪ Increased enzyme accessibility	▪ High heat demand and hence energy consumption ▪ Not effective at all temperature ranges
5	Microwave	▪ Leads to more biogas production by 4%–7%	▪ Increased process energy input ▪ Increases labor and maintenance cost
6	Diluted or strong acid pretreatment	▪ Used to Solubilize hemicellulose component. ▪ Methanogens can adapt to inhibiting compounds.	▪ Acids are expensive. ▪ Can form inhibiting compounds. ▪ Causes corrosion problems.
7	Alkaline pretreatment	▪ Used to solubilize hemicellulose and some lignin. ▪ Increased methane production	▪ Can produce inhibitors. ▪ Can cause high alkali concentration in reactor

Table 10-6 demonstrates the wide range of pretreatment options available, each with its own set of benefits and drawbacks, and cost benefit implications. While pretreatment enhances the efficacy of the process and the biogas yield, it also introduces difficulties such as higher energy input, increased operating and maintenance expenses, and the introduction of inhibitory chemicals.

Anaerobic digesters (AD) have become increasingly popular in producing renewable and sustainable energy from waste. Although synergies do exist between various technologies, the configurations to couple need further development [700].

10.2.4.2. Processes in Anaerobic Digestion

i. Hydrolysis

Hydrolysis is a chemical reaction in which water is broken down into OH^- anions and H^+ cations. In the presence of an acidic catalyst, hydrolysis breaks down the massive biomass polymers present in the substrate[470]. The proteins, carbohydrates, and lipids, all of which are massive organic polymers, are broken down into their component simple sugars, fatty acids, and amino acids to make up biomass [470, 694, 695]. During the process of hydrolysis, fermenting bacteria, such as Bactericides, Clostridia, and Bifidobacterial, efficiently decompose biopolymers, including carbohydrates, proteins, and lipids, into soluble forms such as sugars, fatty acids, and amino acids[701]. Hydrolysis produces acetate and hydrogen, which are put to good use by methanogens in the final stages of anaerobic digestion. Methane formation by acidogenesis necessitates further hydrolysis product breakdown, as these are still quite large molecules [482, 702].

ii. Acidogenesis

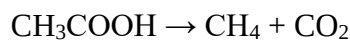
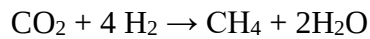
Anaerobic activity of acetogens produces mostly organic acids, alcohols, hydrogen gas, and hydrogen sulfide throughout this process [470, 701]. In an acidic environment generated by the fermentative bacteria, hydrolysis products are degraded by acidogenic microorganisms to produce ammonia, carbon dioxide, hydrogen sulfide, carbonic acid, shorter-volatility fatty acids, alcohol, and other trace products based on the substrate composition and products of hydrolysis [701]. Acidogenesis byproducts are too large to be ideal for methane production. Thus, they engage in acetogenesis [467].

iii. Acetogenesis

The process of acetogenesis produces acetate from acetic acid [703]. Through anaerobic digestion, acetic acid, hydrogen, and carbon dioxide are generated during acidogenesis. The results of acetogenesis and other processes are digested to the point where methanogens can produce methane [467].

iv. Methanogenesis

Methane and carbon dioxide are created in the final stage, called methanogenesis, thanks to the activity of acetoclastic methanogens (AM) and carbon dioxide (CO_2) reducing methanogens (CM), respectively. Finally, anaerobic bacteria called methanogens like *Methanosarcina barkeri*, *Methanosaeta conciliibacteria*, and *Metanococcus mazei* complete the methanogenesis process by producing methane from the byproducts of acetogenesis and other intermediate products of acidogenesis and hydrolysis [470, 481, 701]. The first three stages of methanogenesis involve the utilization of carbon dioxide and acetic acid:



While carbon dioxide (CO_2) might theoretically be turned into water and methane, at this time the acetic acid pathway is the primary mechanism for methane generation. Therefore, carbon dioxide (CO_2) and methane (CH_4) are produced as the primary products of anaerobic digestion via the acetic acid pathway [467]. H_2 and CO_2 gas combinations are transformed into biogas, which is composed of 60–70% CH_4 and 40–60% CO_2 [463]. The four steps of biogas production, together with associated activities and microorganisms, are depicted in Figure 10-4.

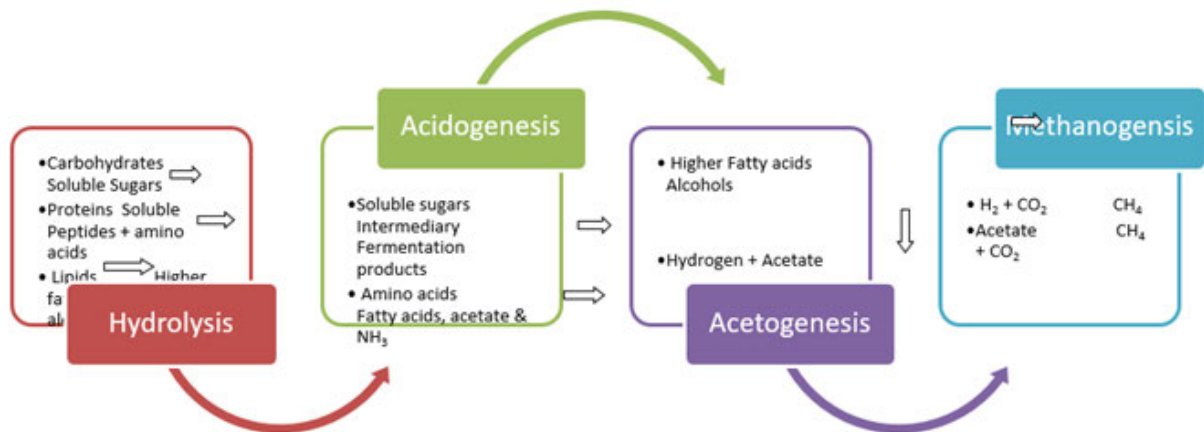


Figure 10-4: Summary of the biogas formation process[474]

Figure 10-4 shows the main stages in biogas production being hydrolysis, acidogenesis, acetogenesis, and methanogenesis as the four primary stages in anaerobic digestion. Maximal biogas production requires careful management of the four main stages.

10.2.5.Factors Influencing Digester's Efficiency and Performance.

There are many factors that influence anaerobic digestion and biogas production e.g. There biogas potential of feedstock, nature of the substrates, inoculums, digestion pH, temperature, digester loading rate, hydraulic retention time (HRT), carbon/nitrogen (C: N) ratio, presence of volatile fatty acids (VFA), presence inhibitory substances, etc. [704].

i. Feedstock

Any biodegradable waste that has fats, proteins, carbohydrates, cellulose, and hemicelluloses is suitable as feedstock in anaerobic digestion. However, the various feedstocks have different theoretical chemical oxygen demand (COD) and the potential biogas. They have different or varied biochemical structure and rate of its biodegradability leading to differences in productivity. The factors in feedstock that influence biogas productivity are Biochemical oxygen demand (BOD), volatile solids, carbon/nitrogen (C:N) ratio Chemical oxygen demand (COD), volatile solids (VS) content, C:N ratio and presence of inhibitory substances [115, 704]

ii. Temperature

The bio-digestive process can be accelerated within tolerable limits by heating process. The same holds true for the processes involved in making biogas. The microorganisms engaged in anaerobic digestion perform both thermophilic and mesophilic digestion. Temperatures between 45 and 80 degrees Celsius are ideal for thermophiles, while those between 25 and 40 degrees Celsius are ideal for mesophiles, yet the Psychrophilic bacteria operate below 25°C [467]. A decrease in methane concentration and a rise in carbon dioxide (CO₂) might impair the heating value of the gas produced if global warming is not controlled. The best number to use for reliable and productive biogas production depends on the organism being used [328, 704].

iii. Digester instrumentation

Anaerobic digesters require continual monitoring of production levels and parameters to ensure optimal process management and, consequently, output is achieved by detecting and responding to changes in biomass quantity, anomalies, and the health of microorganisms [481]. The amount of biomass still to be decomposed and the amount of time spent doing so should be indicated by the gases produced. Knowing when to add new feedstock and the digester's efficiency can be gauged with this information. Maintaining optimal microbial

digestion requires monitoring gas generation in a system where biomass is added regularly [467]. By monitoring the gas produced, issues in the digester, like a shift in pH or temperature, can be identified and remedied [82].

iv. The pH

The pH is an important parameter in the operation of the digester, and the value of pH changes is different at different states of the digestion. Biogas yield is optimized at pH range of between 6.5-7.2[121, 704]. At a pH of about 5, acid-forming bacteria are at their most productive, while methane-forming bacteria thrive at a PH of 6.2 or higher [470]. The bacteria population used in the bio methane process does best between 6.8 and 7.2, but can survive in a wider pH range [705]. When the pH of the digester falls outside of that range, the methane-producing bacteria die. Providing ideal circumstances for the microorganisms responsible for methane synthesis is crucial to ensuring their survival. For the digester to generate the required gas, the microorganism is required. As a result, this requires regular attention [703, 706].

v. Carbon Nitrogen Ratio (C/N ratio)

The Carbon Nitrogen ratio (C/N ratio) determines the suitability of biomass for anaerobic digestion. Where the C/N ratio is high indicates low nitrogen content needed for microbial growth which leads to low uptake of Nitrogen by methanogens needed for protein production. The result is wastage of carbon and low biogas production[113, 704]. The overall carbon to nitrogen ratio of the substrate. Although very high C/N ratios foster population expansion of methanogens, which has little to no influence on the carbon residue in the substrate and results in poor methane output, the optimal ratio for anaerobic digestion is between 20 and 30. Overabundant ammonia reduces methane generation and poses a threat to methanogenic bacteria when the carbon to nitrogen ratio is too low [703].

vi. Toxicants/Inhibitors

Inhibitors (i.e., which are toxic to the anaerobic digestive process) of methanogenesis, such as antibiotics and other residues, result in less methane synthesis and a rise in the concentration of volatile acids. Avoiding a high nitrogen to carbon ratio is important since it increases the likelihood of creating hazardous circumstances for the bacteria [470].

The most common inhibitory substances in substrates for the anaerobic digestion process are carbon dioxide (CO₂), Ammonia (NH₃), Long Chain Fatty Acids (LCFA), hydrogen sulfide (H₂S). Methanogens are more sensitive to toxic material than other groups of bacteria. Short

chain fatty acids being the main inhibitors for methanogens. The concentration of ammonia is important but needs control with less than 200mg/l being suitable for biogas generation. Nitrogen is a nutrient, hence C:N ratio of 30:1 improves biogas productivity by supplying nutrients to micro-organisms for the microbial activity. The methanogenic phase is also inhibited by the effect of ammonia which is rich in swine waste, poultry waste, swine waste, and high proteinaceous sludge. It is the free ammonia (NH_3) and not ammonium ion (NH_4^+) that is responsible for inhibitory effect. Studies show that ammonia with a concentration of 1.77-14 g/l of total ammonia nitrogen can reduce the biogas yield by about 50%. The inhibition by ammonia is influenced by the temperature and the pH. Changes in the temperature and pH can lead to process dynamics disturbance leading to as much as 30% loss in biogas yield. Thermophiles are more sensitive to Long Chain Fatty Acids (LCFA) inhabitation compared to mesophiles. LCFA are found slaughterhouse waste, agricultural residues, olive oil, food waste, wastewater, etc. which act as inhibitory substances in the process of anaerobic digestion[704].

vii. Hydraulic Retention Time (HRT)

The Hydraulic retention time (HRT) refers to the time taken by the biodegradable material in the bioreactor. Factors influencing the Hydraulic retention time (HRT) include the temperature inside the digester, technologies applied, and the type of feedstock used. The recommended HRT for mesophilic digester is 10- 40 days while the thermophilic digester is about 14 days. A very short retention time may have the bacteria washed out of the digester before getting multiplied which leaves the digester in a state of standstill, while longer retention time increases the volume of the reactor to handle the same feedstock. To reduce the retention time and reactor volume, an optimum loading rate should be maintained for optimizing methane production, with 2-3 weeks being regarded as generally optimum for lignocellulosic material to degrade and produce biogas[704].

viii. Co-digestion

The performance of a digester can significantly be enhanced by co-digestion which helps supply the necessary missing nutrients to micro-organisms for higher efficiency. Common materials for co-digestion includes leftover foods, cow manure, vegetable wastes, and fruit. Co-digestion with properly selected feedstock materials can significantly increase biogas yield[704].

ix. Redox Conditions

The digester's Redox conditions dictate the degree and velocity of contaminant biodegradation. Aerobic biodegradation rates are typically substantially higher than anaerobic biodegradation rates for most pollutants. While oil that has settled into anaerobic sediments may be quite tenacious, petroleum-based hydrocarbons that penetrate the aerobic zone of waters in lakes and rivers are susceptible to microbial destruction. Highly reduced hydrocarbons, like the alkanes, have low molecular weights and require oxygen to degrade. Methane and other alkanes cannot undergo anaerobic degradation. Hexadecane ($C_{16}H_{34}$), a high-molecular-weight alkane, may be present in some conditions. These chemicals rarely degrade and are often found in petroleum-contaminated areas. However, heavily chlorinated molecules like perchloroethene (PCE) resist oxygen decomposition. Anaerobic environments can bio transform these substances [707].

For a biodigester, the methanogenic bacteria require redox condition between -300 and -330 mV for optimal performance [708]. Redox condition is important for fermentative H_2 production process in which anaerobic bacteria is crucial and rate limiting. The efficiency with which substrates are metabolized, proteins and other storage resources are synthesized, and metabolic waste products are excreted are all impacted by the Redox state. Pyruvate undergoes an oxidation-reduction reaction (AB) that produces VFAs and H_2 under acidic circumstances. Methane (CH_4) and carbon dioxide (CO_2) are produced by mesophilic bacteria during neutral processes, while solventogenesis occurs during basic operations. The repression of mesophilic bacteria indirectly promotes H_2 producers within the system. The anaerobic bacteria operate below pH 6, but MB optimum range is between 6.0 and 7.5. The pH range of 5.5-6.0 is ideal to avoid both methanogenesis and solventogenesis. Good H_2 is realized at a pH of about 6 compared to near neutral. However, highly acidic pH (<4.5) inhibits H_2 production as it inactivates AB. Hydrogenase enzyme activity gets inhibited by maintaining low or high pH beyond optimum range [709].

x. Mixing Rate

The biogas production plants need an appropriate mixing system to provide favorable conditions for microbial community, for process stability and efficiency in anaerobic digestion. [700, 710]. The mixing intensity or shear rate and the length of time that shear rate is applied to a mixer determines the degree of mixing realized. Application of uniform shear

rate is an important strategy to achieve stability of bio digestion process. In some studies, higher mixing intensity of 67 rpm for 5 min h⁻¹ led to 15–18% higher production output compared 10 rpm and 30 rpm without generating instability in terms of VFA accumulation and dead zones. A higher mixing rate reduces dead zones to less than 2%. Therefore, mixing significantly affects the biogas production rates but the impeller design is the principal factor. The best results were achieved by using a large diameter impeller running at medium mixing rate in anaerobic reactor[710, 711].

xi. Inoculum

The inoculum is used to reduce the start-up time of bio digestion by seeding of the which accelerates biogas formation. By use of inoculum, about 80% biogas can be obtained within the first 10 days of digestion period [704]

xii. Moisture

The substrate dilution or moisture content affects the process of anaerobic digestion with best results in terms of methane yield achieved under 60-80% humidity[386, 704].

xiii. Organic Loading Rate (OLR)

The OLR is the rate at which organic matter is added to the digester volume in relation to either time or the substrate's biological conversion capacity. The organic loading rate is directly promotional to the quantity of volatile solids loaded in the digester and hence it influences the biogas yield, with more methane production for lesser the OLR. If the reactor has higher concentration VFA's, then it implies that it is overloaded [704]. The loading rate of a digester is the daily volume of volatile solids given to the digester, and methane production are favorable with high loading rates [470].

xiv. Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)

The Biochemical oxygen demand (BOD) and the Chemical oxygen demand (COD) affect biogas production too. The biochemical oxygen demand determines the amount of oxygen needed by the microbes to decompose the substrate. If the BOD is high, then a more rapid organic degradation is achieved which leads to more biogas production. The chemical oxygen demand (COD) measures all organic and inorganic biodegradable matter in feedstock or substrate. The value of COD of an organic waste helps predict the theoretical methane yield from the substrate. From experiments, if 0.5 l/gm of COD is removed, the approximate methane production is about 0.35 l/g[64, 704].

10.2.6. Energy Requirements for Biogas Process

The production of biogas necessitates the addition of heat to keep the substrate at an appropriate temperature and the constant stirring of the substrate, either by hand or with an electric motor-driven stirrer [703].

Therefore, process heat energy requirement is determined by the relation.

$$Q_t = M * C * (T_2 - T_1)$$

Where

Q_T = Overall heat required to heat the slurry in Kilojoule (Kj);

M = Mass of the slurry in (Kg);

C = The specific heat capacity of slurry and is expressed in Kj/Kg°C.;

T_2 = Desired digester slurry temperature in °C;

T_1 = Temperature of the digester charge/ slurry in °C,

M = Digester size (V) in $m^3 \times$ density of slurry (ρ) Kg/ m^3 ; Density of slurry (ρ) = (Density of water + substrate density dung)/2; Specific heat of slurry = (specific heat of water (4.2Kj/Kg°C) + specific heat of the substrate e.g., cow dung (2.8Kj/Kg°C))/2 = 3.5 Kg/Kg°C

The digester effluent contains waste heat that can be recovered and used to produce the necessary heat energy. The slurry's input temperature may rise by a few degrees Celsius as a result. This results in a potential 50% reduction in the total heat required by thermophilic digestors [441, 712]. External heating is most effective for digestors of a large or medium size. Comparatively inefficient and approximately twice as energy intensive as central heating. 850 – 1000 W/ m^2 K⁻¹ is the typical range for space heating, and 300 – 400 W/ m^2 K⁻¹ is the typical range for space cooling [712].

Parameters such as microbe species, feedstock pretreatment and biogas purification processes, substrate composition, substrate properties, and ideal reactor conditions must be managed to produce biogas profitably. Further investigation is required and have been actively a high interest area towards the enhancement of biogas production and biogas utilization through the application of engineering, biology/biotechnology, and technical innovations in order to achieve cost-effective biogas production [698, 713].

10.2.7. Biogas Feed Stocks

A wide range of biowaste can be used as substrates for anaerobic digestion for biogas production through. Significant volumes of lignocellulosic waste are generated from agricultural, municipal, and other activities. The most commonly used materials for biogas production are animal manure and slurry, waste water and sewage sludge, municipal solid waste, and food processing and consumption generated waste.[698]. The most used substrates for biogas production are pig and cattle manure, and poultry litter which generally competes with traditional manure. [698, 714, 715]. Sewage sludge generated from wastewater treatment plants is the main feedstock for biogas production in places like Gävleborg region and Sweden while the use manure, food waste and industrial waste have been on the rise, although limited. Horse manure was also widely used as a substrate during co-digestion. Policy measures like ban on the landfilling of organic waste and competing applications like manure use can shift the demand for biogas feedstock selection [715, 716]

The quantity and composition of biogas produced by biomass digestion is a function of the substrate used and process parameters control. Different types of feedstocks can be applied for biogas production ranging from animal wastes, agricultural residues, and energy crops[717]. The various feedstock used have different characteristics and hence biogas potential and hence may require different type and level of pretreatment and process conditions during anaerobic digestion [115, 718]. Feedstock biomass can take the form of a solid, a slurry, or a liquid (either concentrated or diluted). Many different materials can be used as feedstocks, including animal manure, straw, biowaste from homes and businesses, waste from bioethanol and biodiesel production, waste from markets and restaurants, sewage sludge from wastewater treatment plants, and energy crops like maize, silage, grass, sorghum, cereals, and sugar beets. The high lignin concentration of wood makes it unsuitable for anaerobic digestion and biogas production [115, 275, 495, 719].

Several different kinds of biomass garbage can be converted into biogas. Litter from farms, city dumps, and other sources can all contribute to the production of lignocellulosic garbage. Common forms of waste that are utilized as feed stock include animal manure, slurry, sewage sludge, municipal solid waste, food waste, and agricultural waste [698]. The biomass feedstock used to create biogas consists of a wide variety of components, including lipids,

proteins, carbohydrates, cellulose, and hemicellulose. Co-substrates are added to alter the organic composition and boost biogas generation. Most co-substrates consist of organic industrial waste, food scraps, and municipal biowaste. Although lipids generate more biogas overall, carbohydrates and proteins convert more quickly[698]. Both biogas potential and yield are affected by the feedstock and co-substrates used in production, in addition to the process parameters [326, 360, 720].

There are many substrates that are suitable for anaerobic digestion, which can be characterized and classified into four main groups, namely energy crops, agricultural residues, food production wastes, and organic wastes[387, 721]. In the European countries, about 70% bio digestion feedstock comes from the agricultural sector like manure and agricultural residues. According to the European Biogas Association, agricultural wastes account for 40-60% in biogas production in Germany, Cyprus, Denmark, France, Italy and Poland [717]. The residual digestate is a feasible material for use as organic fertilizers, with huge optimization potential leading to increased farm production and profitability. [721]. The various feedstocks for biogas production are discussed below.

10.2.8.Crop Residues for Biogas

Crop residues, a byproduct of crop husbandry, can be put to several different applications. Combustion, composite manufacture, bio-digestion, and animal feed are just some of the ways that waste materials like these can be repurposed. In terms of surplus agricultural products, India yearly produces around 500 Mt (Million tons) [463]. Nearly 70 million metric tons of organic waste are generated annually in the United States of America. Examples of agricultural waste include spoiled food and water [480]. Agricultural crop residues are a serious concern of farmers and cause significant contributors to GHG generation. Primary agricultural residues remain in fields as by-products after harvesting cereal grain straws, wheat (*Triticum*), barley, rice (*Oryza*), corn stalks, stalks, leaves, etc. On the other hand, secondary agricultural residues are products of agricultural resource processing like bagasse, sunflower husks, nutshells etc. Two sustainability issues associated with the use of agricultural wastes for biogas production are the potential competition with feeding in animal husbandry and the probable depletion of organic matter in the soil and nutrients in farmlands [717].

10.2.9. Energy Crops

Energy crops encompass a wide range of plant species that can be classified into two main categories: herbaceous and woody. Herbaceous energy crops include grass, maize (*Zea mays* L.), and raps (*Brássica nápus* L.), while woody energy crops consist of species such as willow (*Salix*), poplar (*Populus*), and oak (*Quercus*). However, it is important to note that woody crops require a specific delignification pretreatment digestion process to be utilized effectively for energy purposes. Lignin, due to its resistance to degradation in anaerobic digestion, presents a favorable characteristic for gasification, incineration, or composting processes when considering woody substrates[326]. Herbaceous energy crops have many important characteristics making them suitable for anaerobic digestion e.g., high solar energy conversion efficiency leading to high yields, need low agrochemical inputs, and have got low nutrient and water requirement due to their extensive rooting system, to hold onto fertilizers and water, and they also have low moisture content at harvest time. Biogas can be made cost effective and high yielding by using crops with perennial growth habits with low establishment costs and fewer field operations and crops providing high biogas output as a feedstock source [717, 722].

10.2.10. Animal Residues

Animal waste is a valuable energy resource containing biodegradable nutrients and renewable energy. However, by practice, most animal waste is deposited off, collected in lagoons or left to decompose in the open land causing environmental hazard [471]. Generally, the term “animal waste” refers to feces, urine, dung, or other excrement, urea, digestive emission, urea, or similar substances emitted by farm animals like livestock, poultry, or fish[275, 386, 723]. Animal waste like manure emit methane, ammonia nitrous oxide, volatile organic compounds, hydrogen sulfide, and particulate matter, which can cause serious environmental concerns and health problem[82, 474].

The primary sources of animal waste commonly encountered include dairy shed effluent, mainly comprising of wash water, urine, dung, residual milk, and waste feed. Additionally, poultry litter, which encompasses water, manure, spilled feed, feathers, and bedding material, is another significant source[34, 360]. Moreover, renderings from slaughterhouses and other byproducts originating from livestock finishing operations contribute to the overall volume of

animal waste. Dairy manure and poultry litter are widely recognized as prominent examples of animal wastes that are extensively be used in largescale biogas energy production [360]. In the past, significant volumes of bovine excrement were subjected to treatment processes and subsequently utilized as a form of agricultural fertilizer, or alternatively, were disposed of through the practice of spreading onto farmland. Nevertheless, numerous countries have implemented rigorous environmental regulations and legislations to regulate the emission of odors, as well as the pollution of surface and groundwater, soil contamination, and nutrient management. These regulations have prompted the adoption of alternative approaches that discourage the disposal of animal manure. Consequently, there is an increasing emphasis on utilizing animal manure in biomass-based production chains, driven by the incentives provided by these regulations [495, 722].

The challenge with poultry waste is high phosphorus (P) run-off to surface water which creates issues like odor and taste problems in drinking water, because of excess algae growth arising from excess phosphorus. For this reason, local land applications of poultry litter are restricted to protect water quality. Poultry waste on the other hand has high methane potential making it an efficient feedstock for biogas production. Slaughterhouses and fish processing factories also generate significant digestible waste for biogas production [115, 722].

10.2.11. Industrial and Process Wastes

Increased demand and consumption of food and industrial produce leads to large scale generation of waste. There is need for proper management of organic waste to minimis harm to the environment like as climate change, ecosystem damage and resource depletion[717]. About one-third of food produced for human consumption globally is discarded as waste, which is approximately 1.3 billion tons of waste per year. Anaerobic digestion of waste prevents the spread of pathogens and environmental degradation arising when waste is carried by to runoff water to basins and drain into the oceans. Anaerobic digestion surpasses thermal treatments technologies for bakery waste such bread, biscuits, donuts, and pizza dough, as wastes like bakery garbage promotes methane production because it includes easily degradable carbs and vitamins [322, 717].

Implementation of anaerobic technologies started with wastewater treatment hence Industrial wastewater is a major source of aquatic pollution that endangers surrounding environments

and ecosystems. Anaerobic digestion of industrial waste is more advantageous than aerobic wastewater treatment since it produces useful biogas, and substantially lowers energy requirement, and generates less sludge that requires disposal. Brewery wastewater, cassava (*Mánihot esculénta* Crantz) starch wastewater, palm oil mill effluent, biodiesel wastewater and bioethanol wastewater (vinasse) have demonstrated significant biogas potential [717].

10.2.12. Biogas and Energy Potential of Various Feedstocks

Many factors affect the potential of feedstocks for biogas and biomethane production like nutrient content, chemical and biological oxygen demand, total and volatile solids (VS) content, carbon/nitrogen (C/N) ratio, and presence of inhibitory substances. The biochemical methane potential (BMP) is the maximum volume of methane produced per g of VS substrate provides an indication of the biodegradability of a substrate and its potential to produce methane *via* AD. BMP data is used in the design of anaerobic digester (AD) parameters for optimum methane production with use of experimental and theoretical methods to establish the BMP [28, 291, 389, 724].

Different biomass feedstock has different biogas potential in terms of both quality and quantity. Table 10-7 illustrates gas yields and methane contents for various substrates after 10–20 days of retention at 30 degree Celsius [471, 474].

Table 10-7: Methane content and gas yield for different biomass [471, 704]

Substrate	Gas Yield (L/Kg Vs*)	Methane Content (%)
Pig Manure	340-550	65-70
Cow Manure	90-310	65
Poultry Droppings	310-620	60
Wheat Straw	200-300	50-60
Rye Straw	200-300	59
Barley Straw	250-300	59

Oats Straw	290-310	59
Corn Straw	380-460	59
Flax	360	59
Hemp	360	59
Grass	280-550	70
Elephant Grass	430-560	60
Sunflower Leaves	300	59
Agricultural Waste	310-430	60-70
Fallen Leaves	210-290	58
Algae	420-500	63

As shown in Table 10-7 there is a wide range in both the quantity and quality of biogas produced from various forms of biodegradable biomass feedstocks. This can also be summarized in Figure 10-5.

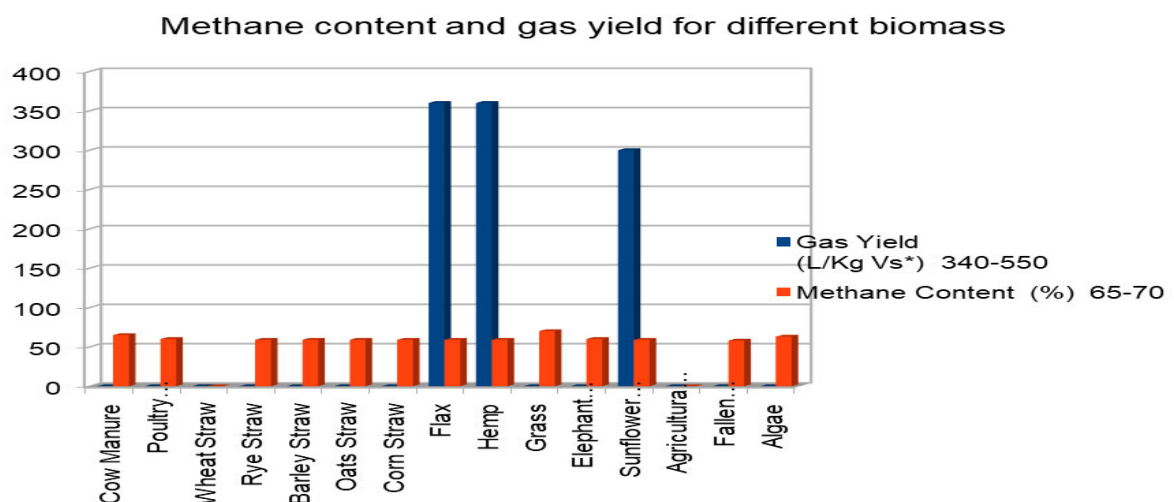


Figure 10-5: Methane content and gas yield for different biomass

From Figure 10-5, it is clearly noted that flax, hemp and sunflower have highest gas yield while cow manure, grass and algae produce biogas with some of the highest methane content.

Biogas can be produced from a variety of sources, including algae, cow manure, pig manure, agricultural solid wastes, and grass. Among the many potential sources of biogas, algae have the highest output, followed by sugar beets, elephant grass, sewage sludge, clover, elephant grass, and maize straw. There isn't much potential for biogas production from materials like reed, sugarcane bagasse, rice seed coat, or rice seed straw. Therefore, a farmer must carefully select his biomass feedstock, or the plants and animals he raises, to achieve maximum biogas output [481].

10.2.12.1. Estimating Energy Potential

According to [481, 725], biogas can be used to generate heat, the cost of which can be roughly calculated using the following formula:

$$E_{pi} = E_m^{cd} * \eta_i$$

Where:

E_{pi} – Production of the energy (heat only, electricity only or heat and electricity in co-generation), [GWh/year]

η_i –efficiency of energy conversion process

E_m^{cd} – Possible production of total biogas energy

Total biogas energy potential from livestock dung can be determined using the following equation:

$$E_m = \sum (N_{i,n} * M_{i,n} * oDM_{i,n} * CH_{4i,n}) * NCV * 365 * 10^{-6}$$

Where:

E_m - Expected production from livestock manure available in the region, [GWh/year]

$N_{i,n}$ --Animals of the same category (cattle, pigs, poultry etc.) in the region, [number of animals]

$M_{i,n}$ - Manure outcome of each category of animals, [kg of manure/animal/day]

$oDM_{i,n}$ -Organic dry matter content in the manure for each category of animals, [%]

$CH_{4i,n}$ -Methane outcome, [$\text{Nm}^3 \text{CH}_4/\text{kg}$ organic dry weight of the animal manure]

NCV – Net Calorific Value [kWh/Nm^3].

10.2.13. Composition of Biogas

Biogas is a mixture of gases with methane and carbon dioxide being the main constituents. Others are carbon monoxide, hydrogen sulphide, hydrogen gas, moisture, and siloxanes. the combustible constituents are carbon monoxide, hydrogen, and methane which produce heat for various thermal, electricity applications[726]. The exact composition of biogas varies from feedstock to feedstock and the quality of the process control. However, biogas mainly consists of methane (CH_4) and carbon dioxide (CO_2)[442]. Pure methane is an odorless gas made up of one atom of carbon and 4 atoms of hydrogen. Methane is lighter than air and is a highly flammable. It can form explosive mixtures with air at concentrations of 5 to 15%. Although methane is not toxic, it can cause death due to asphyxiation through oxygen displacement in confined environments. Methane is a powerful greenhouse gas having ability to remain in the atmosphere for up to 15 years, and is close to 20 more potent in trapping heat in the atmosphere than carbon dioxide for timescale of 20 years [727, 728]. This shows that uncontrolled biogas production and handling is very dangerous to the environment and effort should be made to have controlled bio-deration of organic wastes.

Biogas can be used as a fuel or as a raw material for production of chemicals, hydrogen and/or synthesis gas etc. Other than methane and carbon dioxide as the main constituents of biogas, common contaminants present as trace elements include ammonia (NH_3), moisture, hydrogen sulfide (H_2S), nitrogen (N_2), methyl siloxanes, oxygen, halogenated volatile organic compounds (VOCs), hydrocarbons and carbon monoxide (CO). Some of the trace elements significantly affect biogas as a fuel and must be remove for quality purpose. They include hydrogen sulfide and carbon dioxide. As a fuel, biogas in form of biomethane, biogas upgrading has high operating costs and energy consumption which needs to be addressed [469].

Biogas is a mixture of several gases mainly 50-80% methane, 20-45% carbon dioxide, 2-8% water vapor, effluent and trace gases consisting mainly of O_2 N_2 , NH_3 H_2 H_2S [470, 471]

Table 10-8: Average composition of biogas [442, 470, 473-475]

	Element	Composition (%)
1	Methane	30-80%
2	Carbon dioxide	20-45%
3	Nitrogen	1-10%
4	Ammonia	0-0.05%
5	Moisture	2-8%
6	Hydrogen	0-3%
7	Hydrogen sulphide	0.1-0.5%
8	Oxygen	0.1-3%
9	Ammonia	0-0.5%
10	R ₂ SiO	0-0.5 mg/m ³
11	C _x H _y	0-1%

From Table 10-8, it is noted that methane and carbon dioxide is the main constituent of biogas, and its composition generally varies from 30 to 80% based on the quality of the feedstock and process control.

The main determinant of the heating value of biogas is the composition of methane in biogas. The composition of methane in biogas varies from 45% to 75% by volume [729]. This variation implies that the lower heating value (LHV) of biogas is not constant but varies between 16 MJ/m³) and 28 MJ/m³. Biogas can be used directly to produce electricity and or can be combusted to release heat energy for cooking or perform some work as in internal combustion engines. The desirable characteristics of biogas as a fuel are. The following are

general requirements of biogas engine fuel,

- i.) Should have high methane content.
- ii.) Water and CO₂ composition should be as low as possible for high caloric value.
- iii.) The Sulphur content should be as low since it is converted to acids by condensation and combustion and cause corrosion.

The moisture content can be reduced by condensation in the gas storage or along the gas path while hydrogen sulphide (H₂S) content can be reduced by chemical, biological, or physical techniques [109, 471]. The calorific value of biogas is 5000 to 7000 kcal/m³ and is a function of methane concentration. Generally one cubic meter of biogas is an equivalent of 0.7 m³ of natural gas, 0.7 kg of fuel oil, 0.6 kg of kerosene, 0.4 kg of petrol, 3.5 kg of wood, and 12 kg of manure briquettes, 4 kWh of electrical energy, 0.5 kg of carbon and 0.43 kg of butane [59, 476].

10.2.14. Electricity Potential of Biomass

Different biomass feedstock for biogas production have varying electricity potential as summarized in **Error! Reference source not found..**

Table 10-9: Comparison of biogas yield and electricity produced from different potential substrates[698, 713]

Type		Biogas yield per ton fresh matter (m ³)	Electricity produced per ton fresh matter (kW·h)
1	Cattle dung	55–68	122.5
2	Chicken litter/dung	126	257.3
3	Fat	826–1200	1687.4
4	Food waste (disinfected)	110	224.6
5	Fruit wastes	74	151.6

6	Horse manure	56	114.3
7	Maize silage	200/220	409.6
8	Municipal solid waste	101.5	207.2
9	Pig slurry	11–25	23.5
10	Sewage sludge	47	96.0

Table 10-9 shows the biogas and electricity potential of biomass waste. The conversion is based on 35% electrical efficiency combined heat power, heating value $21 \text{ MJ}\cdot\text{m}^{-3}$, 55% methane content, $3.6 \text{ MJ}\cdot(\text{kW}\cdot\text{h})^{-1}$. [698]. The electricity potential in Table 10-9 can also be summarized in Figure 10-6.

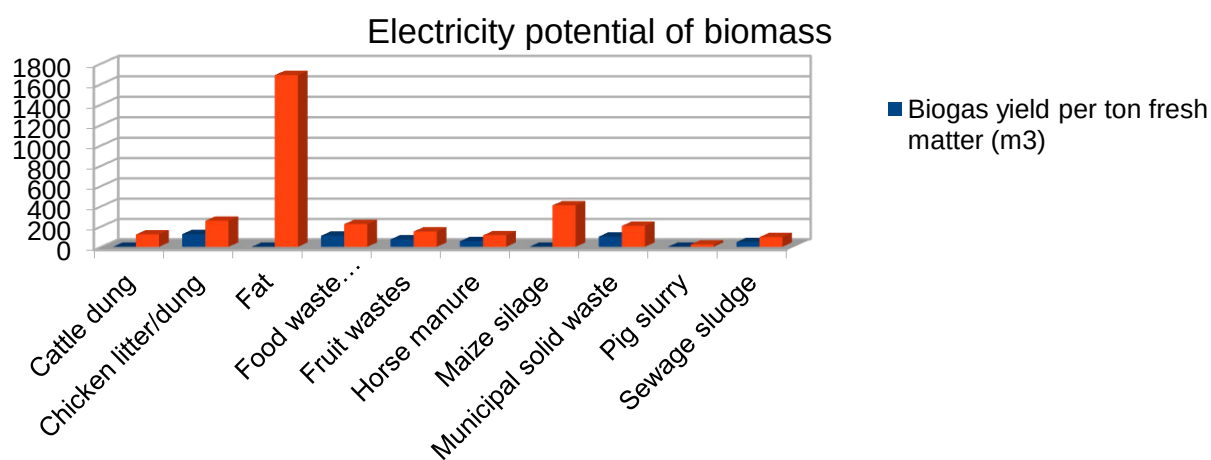


Figure 10-6: Biogas and electricity potential of biomass.

From Figure 10-6 and Table 10-9, it is noted that fat gives the highest biogas yield and has the largest biogas and electricity potential followed by maize silage, chicken droppings and disinfected food waste respectively.

10.2.15. Biogas Applications

10.2.15.1. Fertilizer Application

The composition of the feedstock and the stability of the biogas plant's operations are two

factors that influence the biogas yield, biogas quality, status of digestate, and stability of plant operations [730], and the quality of the sludge from anaerobic digestion, that can be used as an organic fertilizer [468], to improve soil quality, boost crop yields, and aid in the advancement of sustainable agriculture [474]. Biodigester slurry can boost agricultural output by 10-20% by enhancing soil fertility and productivity. It is advised that 5 tons of the digestate be applied per hectare on farms that do not use irrigation, and that 10 tones be applied per hectare on farms that do use irrigation [731].

The chemical and nutrient composition of the biodigester substrate and digestate is determined by the efficacy of the process and the feedstock composition. Very little preparation is needed before spraying the farm with the substrate or digestate or utilizing it as bedding for the animals [480]. Digester slurry is a 25% more effective fertilizer than just putting manure on the farm. This suggests that increasing agricultural yield by employing digestate in this way. In comparison to applying manure directly, biogas slurry makes it easier for plants to absorb the nutrients they need [474].

Slurry from a biodigester can be used as a fertilizer because of its high nutritional content and low environmental impact compared to synthetic alternatives. The digestate can be used as a foliar fertilizer on the farm if it is mixed with water and sprayed on the right leaves. Slurry is collected from the digester via a ditch as gas pressure increases after the biogas plant is refueled with fresh feedstock. Overflow and back pressure can be avoided in a biodigester system with regular ditch emptying by the operator [732]. Digestate consists of water and any unreacted feedstock or co-substrates. Digestate management is necessary for monitoring and controlling biogas production. A farm can either use the digestate as fertilizer or store it in a lagoon or storage tank. The wastewater from a biogas plant that has not been filtered for coarse fiber reduces bio digestion rates and gas production. Bedding and compost can be made from the screened-out material. After fibers have been extracted, the liquid organic residue is known as filtrate. Dry matter nitrogen, phosphorous, and potassium levels in manure filtration concentrate range from 3% to 4.5 %.

The filtrate can be refined into a liquid concentrate and a solid product known as filter cake. Plants' basic nutrients i.e. nitrogen, phosphorous, and potassium, may be found in abundance in these wastes[727]. As a result, biogas generation can be a more economical alternative to

costly chemical fertilizers by boosting agricultural output and yields while saving money for farmers and contributing to long-term energy security. Farmers can earn revenue by selling the digestate or filtrate [360, 607, 608, 733].

10.2.15.2. Summary of Applications of Biogas

Biogas is used in its raw form or is upgraded to biomethane or bio natural gas. The applications for biogas are summarized in Figure 10-7.

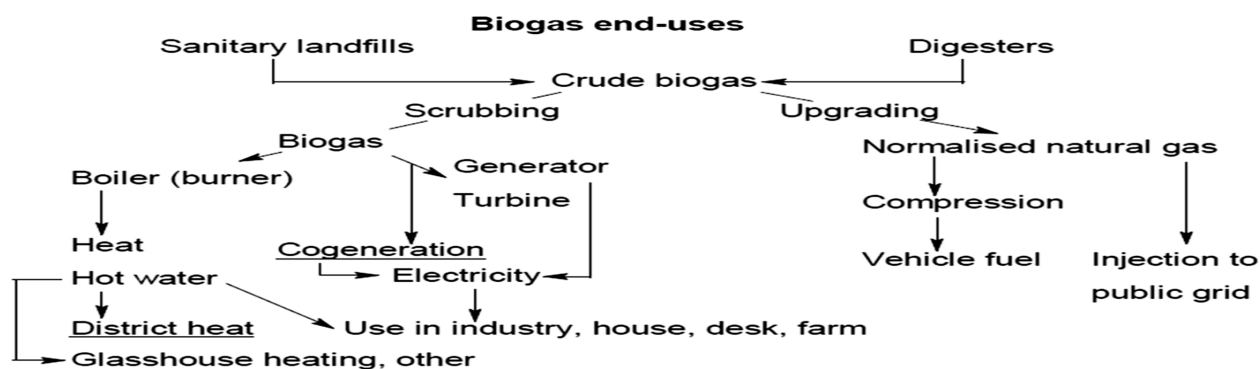


Figure 10-7: Summary of biogas applications in the energy transition.

From Figure 10-7, it is observed that the various energy applications for biogas include upgrading to produce vehicle fuel and injection to natural gas grids, fuel for gas turbines, boiler fuel for heat and power applications among others.

Biogas can be used directly for cooking, and lighting as well as for power generation, but can also be used for production of Fischer-Tropsch (FT) fuels. Fuel upgraded biogas/biomethane which can also be used to process methanol fuel. Compressed biogas (CBG) and liquid biogas (LBG) can reversibly made from biomethane for various direct and indirect application as fuels and power generation. Biogas can be used in processes like combined heat and power generation from biogas (CHP), compression to bio-CNG and bio-LPG for cleaned biogas/biomethane. Fuels are manufactured from biogas by cleaning, and purification before reforming to syngas, and partial oxidation to produce methanol which can be used to make gasoline. Syngas is used in production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process.

10.2.16. Status and Progress of Biogas to Electricity/Energy Conversion

Methane is not toxic, but it can cause death by asphyxiation if not well handled. Therefore,

biogas should be handled carefully. Methane is also a greenhouse and is more than 20 times more potent than carbon dioxide. This implies that leakages by means of accidents or emissions from uncontrolled anaerobic digestion have a significant environmental impact which cannot be neglected in sustainability assessment.

Biogas can also be used in the manufacture of chemical fuels and substances like hydrogen, methanol which can further be processed to gasoline via methanol-to-gasoline process. Other than production of fuels, biogas can also be used as a raw material for production of chemicals whose production process would have led to severe environmental impact. On the negative side, biogas has trace elements like hydrogen sulfide and carbon dioxide which reduce its quality as a fuel. Additionally, biomethane from biogas upgrading has high operating costs and energy consumption which needs to be addressed.

Well designed and built biogas digesters and a wider applications and efficient biogas to electricity, biogas to heat and biogas to value addition chemicals and products will combine to ensure that biogas plays a leading and sustainable role in the energy transition. Electricity from biogas can be used directly which avoids or limits electricity imports from the grid while excess generated electricity can be exported to the electricity grid by using various prime movers like gas turbines, internal combustion engines. It is also possible to make direct conversion from biogas to electricity in fuel cells. Biogas can also be converted to hydrogen fuel for wide renewable applications. This study has identified several pathways for use of biogas in the sustainable energy transition. They are summarized in Table 10-10.

Table 10-10: Summary of biogas to electricity conversion systems and technologies

	Method/ process	Device / technology	Application	Remarks
1	Chemical-electrical	Fuel cell	Generation of electricity	Very efficient, reliable but expensive
2	Chemical-	Hydrogen	Generation of electricity and process chemicals.	Renewable hydrogen process if its biogas or

	electrical		Hydrogen can be produced by steam reforming, dry reforming, or hydrolysis	methane is from renewable resources. Hydrogen is difficult to handle and transport.
3	Chemical	Biomethanation	Biomethane can be fed to natural gas supply and fuel for vehicles and fuel natural gas powerplants	Renewable replacement of fossil natural gas
4	Thermal-electrical	Diesel engine	Can be used in dual fuel mode with diesel fuel for ignition. The engine needs modification to run on pure biogas/biomethane	Diesel engines are more efficient than petrol engines and have more fuel flexibility hence can easily use biofuels.
5	Thermal-electrical	Gas/petrol engine	A petrol or gasoline engine needs little or no modification to run on biogas or biomethane	Less efficient than diesel engines but are easier to convert to biogas fueled engines.
6	Thermal-mechanical-electrical	Stirling engine	Stirling engines are also called hot air engines.	Stirling engines have fuel flexibility and can run on a wider range of fuels
7	Thermal-Mechanical-Electrical	Gas turbine	Can be used as open cycle or combined cycle plants for electricity and heat applications Micro, small, medium, and largescale turbines can be used based on fuel source and	Turbines are versatile and can use raw biogas in uncleaned form. They are light and simple in construction, easy to operate but need skilled manpower.

			application.	
8	Thermal- mechanical- electrical	Cogeneration	Cogeneration is simultaneous generation and application of both heat and electricity from the same fuel source.	Cogeneration can be applied on various conversion systems to increase overall efficiency. Stirling engines, diesel engines, gas turbines, hydrogen and fuel cells can all be operated on cogeneration mode.
9	Thermal- mechanical -Electrical	Trigeneration	Trigeneration is simultaneous generation of electricity with both heating and cooling	Trigeneration is the most efficient conversion system but more complex and expensive

From Table 10-10, it is noted that various conversion technologies with varying characteristics and processes are available for exploitation of biogas in thermal and electricity generation and application. They include cogeneration, trigeneration systems and open conversion systems. Devices or equipment used include diesel engines, petrol gasoline engines, gas turbines, fuel cells, Stirling engines. Feasible energy products for other multiple applications include biomethane and hydrogen fuels.

Biogas has double role to play in reducing emissions from the transport sector which account for close 14% of all anthropogenic greenhouse gas emission. Biogas or biomethane can be used as direct fuel in place of fossil fuels in transport and can also be used to produce biofuels/chemicals through processes like the Fischer-Tropsch (FT) Process to produce jet fuel, diesel and gasoline, and reforming processes (dry reforming, steam reforming, partial oxidation reforming and autothermal reforming) to produce hydrogen and methanol which can be used as a fuel in fuel cells and chemical substitutes as well as direct combustion fuel with very minimum carbon value. Biogas derived transport fuels have very low emissions and, in some cases, have a negative carbon value.

Although biogas has less environmental impacts, it is still associated with some greenhouse gas emissions mainly CO₂, CH₄ and N₂O with the level depending on the technology used or the source of biogas. Therefore, a positive role of biogas in the sustainable energy transition is dependent on the selection of conversion technology used and the source of biogas. The production of electricity from biogas is quite limited in developing countries like African [471]. Anaerobic digestion is used to produce byproducts that are used and hence reduce the negative environmental impact and pollution potential of biogas production. Several benefits of anaerobic digestion are realized by individuals, the human environment, and the whole community [473, 484, 485].

10.2.17. Conclusion

Anaerobic digestion is a biological process where biodegradable matter is degraded to by the action of microorganisms in absence of oxygen to produce biogas, which is a clean fuel from renewable feedstocks with potential use in heat and electricity generation. Factors affecting bio digestion include type of raw materials, temperature, pH, mixing, level preparation and pretreatment, residence time, redox effect, and hydraulic pressure etc. The efficiency of anaerobic digestion can be evaluated in terms of bio-methane potential, gross energy yields, process energy demand, net energy yield, and energy efficiency. Energy crops are the most used substrate for biogas production.

Biogas production is one of the innovative and viable for production of energy from biowastes and biomaterials, with an extra benefit of producing biofertilizer to support sustainable agriculture. Huge quantities of biodegradable waste are generated by humanity globally, which can pose a serious threat to human, animal health, and their environment. There are many wastes disposal and treatment methods employed to avoid environmental pollution. Among the many options, anaerobic digestion is a popular non-conventional energy source used to produce renewable energy from biodegradable biomass.

Biogas is a product of the anaerobic digestion process with many applications as in generation of renewable energy. The main component of biogas with energy value is methane, but has impurities like moisture, carbon dioxide, siloxanes, hydrogen sulphide, siloxanes, hydrocarbons, oxygen, ammonia, oxygen, carbon monoxide and nitrogen whose presence is undesirable as they reduce the calorific value of biogas and create operational problems in the

energy systems. This necessitates biogas cleaning and application of multi-stage technologies to produce upgraded biogas called biomethane. Biomethane gas is a flexible and easy to store fuel with similar properties and applications to natural gas with no need to modify any equipment settings for natural gas devices and equipment.

The factors influencing the process and quality of biogas produces include the C/N (carbon nitrogen ratio, the pH, dilution of feedstock, composition and nutritive value of feedstock, residence period, mixing and stirring, temperature, presence of toxicants, loading time and redox conditions. The main challenges facing biogas production and use include lack of technical training on biogas production and use, lack of subsidies and incentives. Therefore, besides easy access to appropriate and affordable biogas technologies, there is a need for developing a comprehensive policy on construction and operation of biodigesters as well utilization of biogas and sale of biogas energy products and services. Biogas education and exposure, availability of simple and affordable biodigesters and facilitating legal and policy environment are key tools needed to increase the adoption of biogas technology and its sustainable use.

Raw or cleaned biogas which is free from harmful contaminants has significant energy value and applications. The multifunctional uses of biogas produce include the production of biofuels and renewable energies, reduction in greenhouse gas emissions mainly methane and carbon dioxide, reduction in nuisances resulting from odors and flies associated with uncontrolled biodegrading of biomass, economic or financial savings for farmers, sustainable waste treatment and recycling of organic waste, minimization of water and air pollution, rural poverty alleviation, better of social conditions of rural or remote settlements like gender , balance as women who bear the responsibility of looking for firewood are relieved of the struggle and conservation of forests and vegetation cover due reduced use of firewood and charcoal.

10.3. Waste to Energy through Fermentation

This section contains work published in [64, 551] as journal and conference papers on ethanol potential of an operating sugar factory. Ethanol can be produced from carbohydrates such as sugar, starch, and cellulose by fermentation using yeast or other organism making the sugar industry an important pathway for ethanol and energy production. The Sugar industry faces

several sustainability challenges because of market competition and high cost of production in some countries. Diversification into ethanol manufacture from molasses is one of the strategies that can be applied to sustain the sugar industry. In this study, the feasibility of ethanol production by a 3000 tons of cane per day (TCD) sugarcane milling factory from molasses is undertaken. Ethanol can be produced from sugarcane or beet sugar juice or from molasses by a series of stages starting with fermentation of the molasses followed by distillation. Through further distillation and molecular sieve dehydration the purity and quality of the final ethanol product is enhanced and can reach as high as 99% ethanol composition. The main equipment for the process includes the fermenter, boilers, condensers, and distillation columns, design to suit the product characteristics and design capacity of the plant. The analysis showed that ethanol production of a sugar factory with design milling capacity of 3000 TCD is a profitable commercial venture with annual production potential of 12.2896 million litres of ethanol which can generate. The study showed that investment is both technically and economically viable and can be used to improve the financial performance and sustainability of the sugar factory in a competitive market environment. Therefore, diversification into ethanol production is an important strategy in sustaining the sugar industry and can play a role in the global energy transition.

10.3.1.Introduction

Ethanol is produced by fermentation of biomass like sugarcane, wheat, corn, sugar beet and cassava, among others. Most ethanol is produced from sugarcane particularly in Brazil and corn in the United States which cumulatively account for about 35.4 million m³, or about 72% of global production[64, 734]. Ethanol can be produced by the sugar industry as both an energy and economic investment option option[735]. With the global warming, and fossil fuel depletion threats and the struggling sugar industry, ethanol offers multiple benefits to the industry and energy sectors globally[3, 21, 81, 326]. Ethanol can be used as a biofuel option to the use of fossil fuels in transport and power generation [3, 62, 736]. It is one of the cheapest feedstock for ethanol production in over 100 countries sugar producing countries globally. [737].

There is a serious global concern over greenhouse gas emissions and global warming with emissions and climate targets set in the Paris Agreement [738]. These have accelerated the

need for sustainable and environmentally friendly energy sources to replace fossil fuels which are main sources of anthropogenic greenhouse gas emissions[3, 59, 632]. Biofuels have an important role in achieving environmental targets and growing energy demand. For over three decades now, sugarcane has been the main feedstock for largescale ethanol production globally[62, 82, 739]. Ethanol can be blended with gasoline and diesel to reduce environmental impact of fossil fuels and to increase the energy security of non-oil producing countries[740]. In the energy application, about 98 percent of U.S. gasoline has some ethanol mixed typically as E10 consisting of 10% ethanol and 90% gasoline meant to oxygenate fuel and minimise emissions. Ethanol provides premium blending properties due to its higher octane number compared to gasoline[741]. Ethanol is a high-octane fuel which can be used primarily as an additive and extender for gasoline[735]. Ethanol demand as a fuel has been on the rise due to increased use of methyl tertiary butyl ether (MTBE) because of its environmental challenges caused by groundwater contamination as well as in high gasoline prices and energy supply security risks associated with fossil fuels[736].

Ethanol, also called alcohol, ethyl alcohol and grain alcohol, is a colourless, clear liquid used as the principal ingredient in manufacture of alcoholic beverages like beer, wine, or brandy[742]. Due to its solubility in water and other organic compounds it is used as an ingredient in the manufacture of personal care and beauty products, paints and varnishes to fuel[741]. Ethanol is also used in manufacture of drugs, plastics, lacquers, cosmetics, polishes, and plasticizers and in medicine as a topical anti-infective, and antidote for ethylene glycol or methanol overdose [741, 743].

Ethanol can be manufactured from carbohydrates through the process of fermentation with yeast or other organisms[744]. Bioethanol is a promising substitute of fossil fuels in the form of a liquids oxygenated fuel having about 35% oxygen made by microbial fermentation of monomeric sugar derived from carbohydrate which include corn, soybeans and sugar cane[736]. Bioethanol is produced in bio refineries for agricultural wastes. like sugarcane wastes. Sugarcane uses fewer mineral fertilizers and generates huge quantities of bio-waste that can be used in manufacture of several value-added products. Since 70%–80% of agricultural residues are often left in the field, recycling and value addition are pathways to increase the value of agricultural produce with several feasible applications in domestic and industrial sectors for energy generation purposes and other industrial as well as domestic

applications. A significant portion of the sugarcane crop can be used in the manufacture of bioethanol [12, 164, 284, 745].

In the crop year 2019–2020, the global sugar production was 166.18 million metric tons, and about 182 million metric tons for 2020–2021 crop year with the largest producers being Brazil, India, the EU, China, and Thailand[746]. The Sugar factories/mills produce sugar, molasses, and bagasse as the major products and by-products while having significant technical, and economic potential for production of electricity, steam generation, ethanol, and other products [493]. The sugar industry is diversified and integrated and produces brown sugar, white sugar, molasses, press mud, ethanol, electricity, pulp and paper, charcoal briquettes, and other products for it to become sustainable and complete [81, 670]. In many countries, sugar factories are connected to electricity grids for power supply earning them extra revenue, while others have established alcohol distilleries to produce ethanol from cane and even beet molasses for some [81, 747].

The sugar industry in countries like Kenya is currently struggling to survive with high costs of production delayed, payment to farmers and inefficient production leading to high uncompetitive industry that cannot survive in the liberalised market [656, 682]. The sugar industry supports thousands of sugar cane growing farmers and sugar cane factory workers. For some countries like Kenya, the domestic sugar demand is less than consumption. This deficit is met by importing sugar from the international which is much cheaper. Often importers bring in excess whenever an opportunity is granted[747]. Cheap imports have led to closure of many local sugar factories that cannot compete due to inefficiency and high costs of production. Diversification into ethanol production as well as export cogeneration are diversification pathways that can increase financial sustainability of the sugar factories besides producing green energy that society needs during the current energy transition[21, 81].

The objective of this study was to establish the feasibility of diversifying into commercial ethanol production by Nzoia Sugar Company Ltd whose design milling capacity is 3000 tonnes of cane per day (TCD) as one of the strategies to improve the operational sustainability of the loss-making sugar factory operating which can be an important energy pathway.

10.3.2.Sugar Production Process

Sugar cane is an important crop as is grown in over 100 countries even though 10 countries

alone account for over 80% of global sugar production [81, 662]. Sugar cane manufacture involves two main energy intensive operations. These operations are processing of beets or sugar cane to raw sugar and refining of raw sugar. Cane and beet sugar extracts consists of mainly sucrose, polysaccharides, proteins lignin, gums, starches, waxes, and other colloidal impurities. The removal of the proteins and colloidal matter requires addition lime, heating, and clarification processes [747, 748]. Molasses is a syrup residue with sugars that do not crystalize with sucrose as well as other impurities. The composition of molasses is influenced by the sugar cane characteristics and the state of the manufacturing process. Molasses yield varies from 2.5% to 3% of the weight of cane milled while its composition normally varies depending on the cane variety and the production process applied[749].

The global commitment to reduction of greenhouse gas emission and global climate change have generated momentum for use of renewable sources of energy and feedstock for various operations and applications. Biofuels like bioethanol can make significant contribution to towards the achieving environmental and energy sustainability [3, 21, 750]. Ethanol is an important biofuel, globally produced with USA and Brazil leading. In the year 2018, 58 billion litres of ethanol were produced from corn-starch while 28 billion litres were produced from sugarcane[114, 723, 739]. Sugar can remains the main source of ethanol production feedstock for sugar producing countries like Brazil[738]. Ethanol can be blended with gasoline and diesel to modify the negative environmental impact of fossil fuels and to increase the energy security for countries with no fossil fuels but rich in agricultural resources[740]. Ethanol has high octane value, making it a good additive and extender for gasoline fuel. Ethanol is produced from carbohydrates like sugar, starch, and cellulose by fermentation with yeast or other organisms[100, 744].

10.3.2.1. Molasses Composition and Properties

Sugar cane molasses is a thick, black or brown sugary syrup produced during the crystallization of sucrose in sugar manufacture [749]. The main advantage of molasses is that it is easily available at industrial scale as a feedstock for manufacture of ethanol. The applications of molasses are many and include manufacture of beverages, acetic acid, glycerol, baker's yeast, and lysine, fertiliser, and animal feed [57, 81]. The composition of molasses varies considerably based on non-sucrose elements in the raw juice and the

technology used in sugar production. Molasses contains about 75–85% total solids, 30–36% sucrose, 10–17% (fructose + glucose), 10–16% ash. Additionally, it contains some small quantities of oligosaccharides, polysaccharides, organic acids, nitrogen compounds and proteins. Molasses contains approximately 50% fermentable sugars making it an excellent feedstock for ethanol production through fermentation. The main difference between sugar beet molasses and sugar cane molasses is molasses from beet sugar has lower concentration of reducing sugars but higher in sucrose content [326, 734, 737].

10.3.2.2. Ethanol Production from Sugarcane Molasses

Alcohol can be manufactured from sugary feedstock through of fermentation process. Fermentation was initially crude and less detailed leading to low production levels and low quality of alcohol produced. Advancement in ethanol technology, better production methods and systems have been developed leading to higher production output and conversion efficiency. Other important developments are use of feedstock with higher ethanol yield than the earlier conventional feedstock[747]. Ethanol production from sugarcane begins with cane milling to produce juice which can be directly used for ethanol production or production of sugar first then using molasses as the feedstock. The direct application involves collection of juice and delivery to the fermentation tank where the yeast fermentation generates ethanol[751]. Sugarcane molasses can be used as bioethanol production by fermentation done by various microorganisms like *Saccharomyces cerevisiae*[752]. The main products of fermentation are ethanol, water, and carbon dioxide (CO₂) which are separated through process of fractional distillation, gas scrubbing and additional purification produce high quality ethanol.

Bioethanol is made from molasses by simultaneous Saccharification and fermentation (SSF) method which uses 10% substrate (100 gr / L molasses) and 20% substrate concentration (200 gr / L molasses). Molasses hydrolysis done biologically using *Aspergillus niger* and *Trichoderma viride*, while fermentation applies the consortium *Saccaromyces cerevisiae*-*Pichia stipitis*. The SSF methods have highest bioethanol concentration of 14.38% v/v for 20% substrate and 10% consortium usage at 72 hours fermentation[742, 753]. Although molasses has got high composition of fermentable sugars making it a good feedstock for ethanol production, it has high a very high pH making it unsuitable for microbial activity. This

makes pre-treatment or preparation necessary before injection into the pre-fermentation and fermentation chamber to lower the PH. The most common preparation methods include acid dosing to lower pH to 4-5 and dilution to lower concentration of sugars to 10-15% which are optimal conditions for microbial activity[753].

After fermentation, ethanol produced is mixed with water and carbon IV oxide gas which must be removed by fractional distillation and gas scrubbing respectively to yield higher quality ethanol. Figure 10-8 shows the summary of ethanol production from sugarcane molasses.

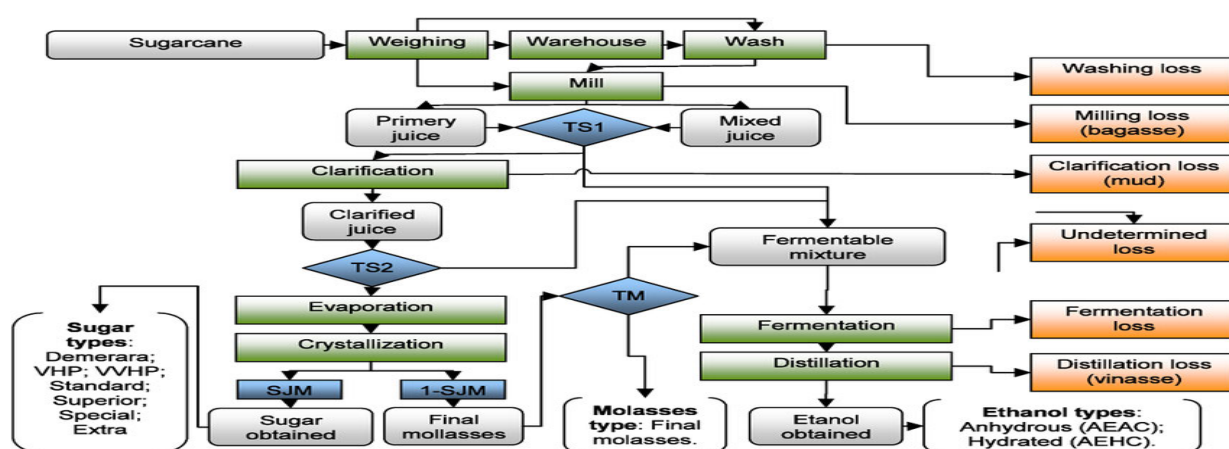


Figure 10-8: Ethanol from Molasses Flow Diagram[749, 753]

From Figure 10-8, it is noted that the process of ethanol production can be summarised as pre-treatment to remove lignin or hemicellulose and liberate cellulose; depolymerization of carbohydrate polymers to produce free sugars by the action of cellulase mediated process; fermentation of hexose and/or pentose sugars to which produces ethanol; followed by distillation to produce alcohol[742]. Ethanol from sugarcane molasses is a feasible alternative for partial replacements of fossil fuels. The use of bioethanol contributes to the climate change mitigation by reducing greenhouse gas emissions by blending with fossil fuels[754].

Almost all plant-based material can be converted to ethanol since all plants contain sugars which are fermentable and can be used to produce ethanol through biochemical conversion or using heat and chemicals in a process called thermochemical conversion [755]. Most of the ethanol produced globally is derived from starch- and sugar-based feedstock. The sugar in the feedstock should be easy to extract and ferment for the feedstock to be suitable for largescale

ethanol production. Corn is widely used in the United States for most domestic and industrial ethanol production. Other commonly used feedstock are cassava, millet, sorghum, bagasse among others[755, 756]. The feedstock selected vary depending on availability, alternative/competing uses, percentage of fermentable sugars present and the cost of the feedstock.

10.3.2.3. Components/Parts of a Distillation Column and their Functions.

The distillation or fractionation column has many parts and functions. They include the stripping Section which consists of trays between the bottom of column and the feed tray used to concentrate heavier content in liquid phase. The second part is the rectifying section which has trays between the feed tray and the top of the column and whose main function is concentrate the lighter component in vapour phase. The third section or part is the reboiler: a heat exchanger at the bottom of the column which boils some of the liquid leaving the column. The vapour generated returns to the column at the bottom of stripping section[757]. The factors affecting operation of distillation column and contribution towards overall efficiency include feed conditions, internal fluid flow conditions, State of trays or packing and the atmospheric weather conditions.

10.3.2.4. Overview of the Design

A basic ethanol plant contains molasses storage tanks, fermentation tanks, yeast culture tanks, distillation columns, aldehyde separation columns, molecular sieve dehydration chambers and ethanol storage tanks all performing roles explained and discussed. The flow diagram is as shown in Figure 10-9.

From Table 10-11, it is noted that the factory has never made profits between the year 2013 and 2017. The factory has realised operational losses since 2013 because of challenges like high cost of sugar production in a market flooded with cheap sugar imports. The records indicate that last time the company realised a profit of ksh.720 million after tax was the year 2012. Sugar production alone is evidently not a profitable undertaking hence the need for diversification. The audit reports from the Auditor General Reports of 2016 and 2017 financial years, Nzoia Sugar records a shareholder's deficit of ksh.31.76 billion and ksh.34.195 billion respectively and also notes current liabilities exceeding current assets by about 40 billion in both 2016 and 2017[81, 326].

10.3.3.Ethanol Plant Feasibility

The alcohol potential of a sugar factory is a function of molasses produced and conversion efficiency from molasses to ethanol. Table 10-12 is used to quantify the molasses and ethanol potential of the factory[64].

Table 10-12: Alcohol production potential

	Rate	Daily
1 Cane crushing capacity	3000 TCD	
2 Optimum molasses production	Cane produces about 4.817% tons of molasses	144.51 Tons of molasses/ day
3 Volume of molasses produced	Density =1200 kg/m ³	120.424 m ³ /day=120.424 kL/day
4 Percentage of fermentable sugars in molasses	52.5%	52.5% of 144.51 tons =75.87 ton/day
5 Alcohol yield	Alcohol yield $A=FS*Y_f*E_{de}$	Yield= 75.87x 0.985x 0.573=42.821 kL per day

6	Average Milling days	Average from plant operations	287 days per year
7	Annual production	42.821 kl/day x 287 annual milling days	12.2896 million litres

Where alcohol yield, $A = FS * Y_f * E_{de}$, where Y_f =fermentation efficiency and E_{de} =alcohol recovery.

Under optimal operations, acceptable values of yield are:

$$Y_f = 57.3\% \quad E_f = 89\% \quad \text{and} \quad E_{de} = 98.5\%.$$

From Table 10-12, it is noted that the factory milling capacity is 3000 tons of cane per day and hence daily molasses capacity 144.51 tons that can produce 42, 821 liters of ethanol per day. Since the factory mills for an average of 287 days per year, the annual alcohol capacity of the 3000 TCD Nzoia Sugar factory is 12.2896 million liters of alcohol per day.

10.3.4.Results and Discussion

Ethanol has several positive impacts like the elimination of lead compounds from gasoline in transport sector, reduction in greenhouse gas emissions. Ethanol as a fuel leads to better air quality in urban areas as well as rural areas [734]. The challenges of large-scale ethanol production from sugarcane or molasses is damage of high-biodiversity areas, soil degradation in cane production from use of chemicals and decarbonization, and deforestation, degradation or water resources contamination or depletion, competition between fuel and food production, which threatens food security and a worsening of labour conditions on the fields [738].

A litre of ethanol costs about ksh.70 (US\$ 0.7) in the Kenyan market while the normal conversion is such that One tonne of molasses yields about 220 litres of ethanol and costs about KES1500 (US\$ 1.5). On average basis the value of ethanol produced is about 10 times the market value of molasses used in the production. With the cost of sugar production in Kenya being about KES50,000/Ton (US\$ 500/ton of sugar) compared to other African companies at an average low of ksh.25000/Ton (US\$ 25), the Kenyan sugar is not competitive

and hence the need to diversify into ethanol and generate extra revenue streams and profits for the factories making them more competitive [64, 738].

A good project is one that quickly pays off its invested capital hence projects with shorter payback periods are preferred. Period taken for summation of discounted net revenues to equal cost of investment is called payback period. The lesser this period, the better the profitability. As can be seen, it takes an investment of \$137.46 to produce 1000Liters of ethanol. At the rate of 1litre of ethanol=\$ 0.7, 1000L of ethanol=\$700[141, 758]. The business performance analysis of the proposed ethanol plant is presented in Table 10-13.

Table 10-13: Business performance

	Benchmark parameter	Formular	Value
1	Ethanol production per year	220 liters/ton of molasses	12.2896 million/year
2	Estimated price per liter	US\$ 0.7	US\$ 8.60272 Million
3	Cost per liter	US\$ 0.13747	US 1.689451312 million
4	Gross profit per liter	Gross profit =0.700- 0.13746=0.5654 US\$/liter	US\$ 6.913268688 million

From Table 10-13, it shown that the gross profit of the ethanol project is about US\$ 6.9 million. Careful selection of process equipment and cost-effective operation and maintenance will ensure a significant return on investment.

10.2.3. Results and Discussion

Ethanol production from sugarcane by products is receiving is important due to significant potential for conversion to sugars and fuels. Ethanol can be produced from sugarcane juice, molasses, and sugarcane bagasse for use as boiler fuel to meet the steam and electricity demand of the sugar factory. In this study, focus was the production of ethanol from molasses

since bagasse and juice have other applications already, but molasses is disposed to the market for different applications by buyers.

Industrial production of bioethanol will sustainably put into use molasses which in the current state is considered as a waste or by product of the main process which is ethanol sugar production. Developing an ethanol plant will add significant value to the factory, increase product range and revenue stream, create jobs and improve competitiveness of the entire investment.

10.3.5.Sustainability of Ethanol in the Energy Transition

Sugarcane ethanol is a renewable fuel since it requires a small amount of fossil fuel for use. The high yields in sugarcane production and high biofuel process conversion efficiency, use of sugarcane-based bioethanol reduces greenhouse gas emissions significantly compared to use of fossil fuels (gasoline) in transport. According to the United States Environmental Protection Agency (EPA), sugarcane ethanol is classified as advanced biofuel that can reduce emissions by 61% compared to gasoline. The CO₂ released from the burning of ethanol was absorbed via photosynthesis by the sugarcane plants during their growth. The use of ethanol has made significant contributions to reducing GHG emissions in Brazil. Denaturants are usually added to ethanol to make undrinkable [759, 760].

Despite being renewable and clean compared to fossil fuels, sugarcane ethanol can generate several negative impacts throughout its lifecycle. These include environmental impacts from the use of land (leading to deforestation and degradation), competition with food crops, air pollution and health risks from harvesting and processing techniques, and poor working conditions.

However, expansion of agricultural land to cultivate crops is the irreversible conversion of virgin ecosystems, since deforestation, for example, can cause the extinction of species and their habitats, and cause loss of ecosystem functions like biomass production and conservation of genetic diversity. Wide-scale destruction of forests affects the hydrological cycle and the local climate, leading to reduction in regional precipitation and increases in regional temperatures. Land currently used for sugarcane plantations occupies was once forest land [759, 760].

10.3.6.Conclusions

Like other biomass and biofuels, ethanol production and use contribute to rural development, through job creation, additional revenue for farmers and sugar industries, and hence contributes to sustainability of natural resources, and reduction of greenhouse gas emissions in a more cost-effective way. The performance analysis of Nzoia Sugar company showed that the factory is technically insolvent because of successive losses from sugar production and sale as the core business. This implies that the sugar manufacturing business alone is not profitable due to high costs of production in a liberalised and competitive sugar market. Therefore, diversification into export cogeneration and value addition to molasses by-product can improve the financial position of the factory.

This study revealed that the factory sales raw molasses as a means of economical disposal which generates little revenue as compared to the value of potential ethanol production from the molasses. It was established that One ton of molasses can produce about 220 litres of ethanol, while a ton of cane milled can produces molasses equivalent of 4.817% cane milled. This implies that an ethanol plant is ten times more financially beneficial than just selling molasses produced based on prevailing market sales rates.

This study showed that ethanol production by the sugar factory with design milling capacity of 3000 TCD is a profitable commercial venture with annual production potential of 12.2896 million litres of ethanol which can generate.

Large-scale consumption of ethanol by countries like Brazil has enabled the saving of millions of tonnes of GHG emissions by replacing gasoline with a renewable fuel improving the national energy security and reduction of external debts, providing employment and addition to the gross domestic product of sugar and ethanol producing countries.

10.3.7.Recommendations

Fermentation is a sustainable waste to energy conversion pathway with significant socioeconomic benefits like sustaining the sugar industry, job creation, boost to local economy. Ethanol can be blended with petrol to reduce environmental impact of fossil fuels. Fermentation and ethanol to energy technologies are mature and available making fermentation a technically sustainable energy transition pathway as demonstrated by Brazil where ethanol blending in gasoline has been increased to 30% from 27% leading additional

3.5% of the country's recoverable sugar to make ethanol and 90% of the country's ethanol comes from sugarcane. Therefore, countries globally should put in place measures to encourage ethanol production and use as an energy option that can reduce emissions by as much as 61% compared to use of petrol.

10.4. Slaughterhouse Waste to Energy

10.4.1.Overview

Slaughterhouses produce huge quantities of different solid wastes and wastewaters which must be treated and disposed of to prevent health and environmental disasters and compliance with the environmental legislation. Waste disposal costs are high while the various processes have high electricity and heat energy demand hence the need for cheap sustainable energy sources. A performance analysis of an operating slaughterhouse was carried out with the objective of identifying challenges, opportunities and improvement measures through operation and proposal of an optimum design of the biogas plant. The facility slaughters an average of 200 cows and 400 sheep per day producing an average of 16,000 kg of solid waste and 40 m³ of wastewater. The study showed that out of the total solid and liquid waste of about 56,000 kg from the slaughterhouse, only 2,800 kg is utilized in biogas production leaving out 53,200 kg of waste untreated by the biogas digester. This research proposes the construction of an 80 m³ capacity hydrolysis tank, 1,600 m³ capacity digester tank and a 2,000 m³ biogas storage bag for increased biogas production. Retention time would have to be increased to 20 days from 17 days and substrate PH level increased to 7.0 from an average of 6.5. The proposed design will increase biogas production from the current 35 m³ to 1,920 m³ and increase solid waste utilization from 1.875% to 75% and that of liquid waste from 6.25% to 100%. Production of biogas and electricity will contribute to greenhouse gas emissions mitigation as one of the wastes to energy pathways in the energy transition. The study concludes that slaughterhouse waste to energy conversion has an important role to play in the sustainable energy transition and a cleaner environment.

10.4.2.Introduction

Slaughterhouses have many processes that are energy intensive that require electricity and heat for operations. They also encounter high waste disposal costs for the various animal by-products (ABP) which makes both energy and disposal costs the main cost drivers in abattoirs

[761]. Environmental regulations in the European Union and other countries require comprehensive treatment and disposal of slaughterhouse wastes, yet the abattoirs produce huge quantities of wastes that must be treated using various acceptable techniques [762]. Animal husbandry and slaughterhouse waste have significant potential for biogas production and generation of an extra revenue stream and supply of energy for internal use [441, 763]. Countries need access to sustainable energy resources for sustainable development and economic prosperity with energy being used to improve the quality of life. Energy is an important input as a factor of production and hence it affects the cost of production of goods and services. Energy is also needed to realize almost all the Sustainable Development Goals (SDGs) [109, 410, 764]. Conversion of slaughterhouse waste to biogas and electricity reduces the cost of waste treatment, inactivates pathogens and production of fertilizer in addition to clean electricity and heat for use in the facility with excess electricity for sale to the public grid hence creating additional revenue stream and plays a significant role in the energy transition to low carbon electricity and energy mix [81, 765]. Waste to energy conversion reduces the over-reliance on fossil fuels for heat and electricity applications [764, 766].

There is a global increase in demand for renewable sources of energy because of commitment by various nations to reduce their carbon emissions [81, 518]. Abattoirs produce wastes that are rich in organic contaminants and nutrients hence have huge potential for recovery of waste and energy generation through biodegrading and anaerobic digestion [767]. A common practice in many countries is to use human and organic waste to produce biogas for heat and electricity applications [768]. Similarly, slaughterhouse waste like blood, hind gut, fat scrubber content, and stomach content which is not meant for further processing of useful products can be used for production of biogas which then can be used to produce hot water and electricity for use in the facility with excess electricity being sold to the grid [765]. With the current global effort to fight environmental degradation and climate change due to greenhouse gas emission in energy and power generation, need for enhanced global food security and stable ecology to realize sustainable development [21, 769, 770], there is growing shift and need for green sources of energy and waste to energy conversion systems [21, 518]. Abattoirs generate significant quantities of waste which can pollute the environment and present significant health and environmental risks [437, 771]. The bio-digestion of the abattoir waste is an important disposal strategy for slaughterhouse waste [607, 608]. The biogas yield

is influenced by a number of factors like the pH, substrate characteristics, C/N ratio (carbon to nitrogen ratio), hydraulic retention time and substrate mixing and digestion temperature [772]. The process produces biogas which can be used for heating and as fuel for biogas engine generators for electricity generation as well as digestate which can be used as organic manure [607, 773]. A typical slaughterhouse needs electricity for lighting and light machines operation and hot water for cleaning. Production of biogas from the waste will bring significant benefits in terms of savings in electricity bills for lighting and heating while excess power and even biogas can be sold thus creating additional revenue streams [438, 766]. Therefore, with concerns over climate change and a clean environment and scarcity of clean energy resources, slaughterhouse waste to energy conversion is an attractive option in the energy transition [101, 330, 769, 774].

Most developing countries have a serious challenge with disposal of slaughterhouse waste. As a result, the waste is disposed of in open dumpsites while liquid waste is disposed in open channels and surface water bodies like rivers which endangers aquatic and human life [608, 728]. Some is released to wastewater system often untreated hence further overloading the poorly managed system. Slaughterhouse waste can increase in the biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids, the pH, the temperature, water turbidity, and deoxygenation of water bodies [437, 775].

The overall objective of establishing the biogas plant at Nyongara slaughterhouse facility was to generate biogas for use in electricity generation besides treatment of slaughterhouse waste to mitigate environmental pollution and meet environmental standards imposed by National Environment Management Authority (NEMA) [775]. The generated electricity was meant to fully supplement the power supply from the utility company i.e. Kenya Power [766]. The electricity bills before installation of biogas plant stood at KES 30,000 (US \$ 300) monthly. The problem of high electricity bills was however not completely solved as the, the slaughterhouse continued to purchase power from Kenya Power at the average cost of KES 10,000 (US \$ 100) which was much lower than the initial average bills [608]. This is a clear indication that the plant is not efficient enough to meet the energy needs of the slaughterhouse as initially anticipated. Additionally, amount of the effluent still flows into the Kabuthi River which is a tributary of the Nairobi River hence the challenge of environmental pollution still exists [608, 766].

10.4.3. Anaerobic Digestion of Animal Waste

The anaerobic digestion of slaughterhouse waste involves of treatment of the animal by-products while at the same time producing useful energy in the form of biogas that can be used for electrical and thermal applications while the substrate or solid waste can be used as a fertilizer to improve crop husbandry [776]. It is defined as a biological process by which organic or biological wastes is digested in oxygen deficient environment to produce biogas and sludge. Inactivation of pathogens is the main concern over anaerobic digestion of abattoir waste. The solution to this serious concern with legal and health implications is to carry out secondary heat treatment process of feedstock by processes like composting, pasteurization, and maintenance of minimum residence period for the digestate as an additional measure [774, 777]. Different countries may have different requirements for treatment of biodigester feedstock for anaerobic digestion. For example, the Swedish law requires biogas plants that use animal waste to pasteurize the incoming substrate at 70 °C for one hour before digestion.

Anaerobic digestion can be done under mesophilic or thermophilic conditions where digestion is done at an average temperature of 35 °C for mesophilic and average of 60 °C under thermophilic conditions. They therefore require different residence conditions to destroy or denature pathogens. The hydraulic residence time for mesophilic process will typically run for 15–30 days, while a thermophilic process has hydraulic residence time of 12–14 days. The advantage of mesophilic anaerobic digestion is that it is less sensitive to changes in process parameters as compared to thermophilic processes. However, the gas yield is lower and with a greater pathogen risk. The main challenge of anaerobic digestion of waste is the methane producing microorganisms are quite sensitive to thermal changes and variations as low as 2 °C can cause adverse effects on mesophilic anaerobic digestion processes. Comparison of mesophilic and thermophilic processes shows that thermophilic anaerobic digestion is superior and hence preferable because the process yields higher methane output, higher waste throughput, and a better pathogen inactivation capacity compared to mesophilic anaerobic digestion. However, the thermophilic digestion process is expensive and requires a higher degree of process monitoring compared to mesophilic anaerobic digestion [776]

10.4.4. Conclusion

Slaughterhouse operations generate huge volumes of organic wastes which include dung, fats,

blood, animal trimmings, urine, and paunch contents. Slaughterhouse waste should be carefully handled and processed because are a potential source of bacterial, prion, viral, and parasitic pathogens, that can infect humans and animals. Disposal methods include composting, rendering, anaerobic digestion (AD), alkaline hydrolysis (AH), incineration and incineration. Slaughterhouse waste especially that with high fat and protein of slaughterhouse is excellent substrate for anaerobic digestion processes that leads to both disposal, nutrient recycling, and in methane generation. Slaughterhouse waste can pollute air, soil, and water if disposed of untreated or poorly managed. This study demonstrates the potential of abattoir waste in the energy transition to renewable energy and low carbon electricity. The performance of operating slaughterhouse was used as a basis feasibility assessment. The composition of slaughterhouse waste was presented, and production output estimated under current and optimal conditions. Slaughterhouses can meet their own internal energy use and export excess as biogas, biomethane or electricity. This will earn extra revenue, mitigate greenhouse gas emissions by displacing fossil fuel sources and solve the challenge of waste treatment and disposal.

10.5. Waste Heat Recovery in Geothermal Power Plants

This section contains work published in paper [332] co-authored Prof. Oludolapo. The study investigated the feasibility of waste heat recovery from used brine of a flash power plant using an organic Rankine cycle. Organic Rankine cycles are the best thermodynamic cycles for application in low temperature heat energy sources. Most geothermal power plants globally use the single flash technology to produce electricity. Depending on the thermodynamic conditions, it is possible to install an organic Rankine plant as a bottoming plant to a conventional geothermal plant. In this study, is an organic Rankine plant to utilize waste heat in used geothermal fluid living flash stations SD2 and SD3 for Olkaria Power station in Kenya is proposed. The study showed that up to 73.9MW power can be generated from waste brine for Olkaria IV geothermal field before reinjection in. The main objective of this study was to develop an ORC plant running to generate electricity from brine leaving flash tanks to reduce energy wastage in brine and on n-pentane as the working fluid installed on this brine stream will have a gross capacity of 7.6 MW.

10.5.1.Introduction

There is growing interest in efficient recovery of waste heat and low temperature energy resources like geothermal, solar and ocean thermal for maximum generation and cost reduction in power generation which will also reduce on fuel consumption and environmental pollution from waste heat and fuel combustion. Binary cycles like Organic Rankine, Kalina and Goswami cycles in different designs have emerged as more efficient options for efficient recovery of heat from low-grade heat sources. Geothermal power plants like other thermal systems generate waste heat which depends on the conversion technology. Various opportunities exist for waste heat recovery in many industries like cement, steel, glass, and vehicles industries as well as internal combustion engines to realized higher efficiencies[332].

10.5.2.Materials and Methods

Various components are employed in heat exchangers, and likewise a wide range of materials used in the manufacture. The heat exchanger components and materials used is influenced by the type of heat exchanger and desired applications. The common components of heat exchangers are shells, spirals, tubes or coils, plates, fins, and adiabatic wheels. The materials used for heat exchanger components varies with design requirements, but the choice is guided by strength and thermal conductivity. The common materials used are, titanium, stainless steel , heat exchangers, graphite, composites, ceramics, and plastics[778, 779].

10.5.2.1. Types of Heat Exchangers

Heat exchangers come in different designs with varying performance characteristics, cost and efficiencies [780]. The common types of heat exchangers are Shell-and-tube, Finned tube, Bare tube, Plate-and-frame, Spiral and Plate coil types[780]. Shell and tube heat exchangers are the most common type of heat exchangers. They are built with a single or a series of parallel tubes (tube bundle) which are normally enclosed within a sealed, cylindrical pressure vessel called the shell[780]. The operation is such that one fluid flows in the tube side while the other flows through the shell during the heat transfer[778].

The shell and tube type heat exchanger were selected for the condenser, preheater, and evaporator due to its advantage over the other types of heat exchangers. The following reasons accounted for selection of the type of heat exchanger:

- i.) The tube and shell heat exchangers give very large surface area due to their design.
- ii.) Are simple to fabricate,
- iii.) Are easy to clean.
- iv.) Are adapted for high pressure vessels.
- v.) Can be made from several engineering materials.

It consists of a shell which is usually a large pressure vessel with bundle of tubes running through it which increases the surface for heat exchange and baffles provided on shell side to support the tubes, uniformly maintain spacing between the tubes as well as directing the working fluid flow to enhance heat exchange[781-783].

10.5.2.2. Heat Transfer Coefficients

The heat transfer coefficients vary between the type of primary and working fluids used. [784, 785]. Table 10-14 shows the overall heat transfer coefficients for different fluids.

Table 10-14: Heat transfer of different fluids [784, 785]

Heat From	Transfer To	Overall Heat Transfer Coefficient($\bar{U}$) W/m ² . k
Ammonia (condensing)	Water	850-1400
Propane or butane (condensing)	Water	700-765
Refrigerant (Condensing)	Water	450-850
Refrigerant (Evaporating)	Brine	170-850
Refrigerant (Evaporating)	Water	170-850
Steam	Gases	30-285
Steam	Water	1000-3400
Steam (Condensing)	Water	1000-6000
Water	Air	25-50
Water	Brine	570-1135

From Table 10-14, it is noted that different fluids have different overall heat transfer coefficients. Heat transfer coefficient from ammonia to water is the highest followed by heat transfer between steam and water, while water to air is the lowest.

10.5.2.3. Calculation of Heat Transfer Areas

The heat transfer in a heat exchanger is governed by the equation, $Q_e = \bar{U} \cdot A \cdot \text{LMTD}$, where $\bar{U}$ is the overall heat transfer coefficient, A is the total heat transfer area of the heat exchanger surface while LMTD is the log mean temperature difference

$$\text{LMTD} = \frac{(\Delta T_A) - (\Delta T_B)}{\ln \left[\frac{(\Delta T_A)}{(\Delta T_B)} \right]}$$

Where ΔT_A and ΔT_B refers to temperature difference temperature of the two fluid streams at the entry and exit designated as A and end B, respectively.

10.5.3. Organic Rankine Cycle Design

The main elements of the organic Rankine cycle are the feed pump, the evaporator, the turbine, and condenser. Figure 10-10 shows the basic Organic Rankine cycle.

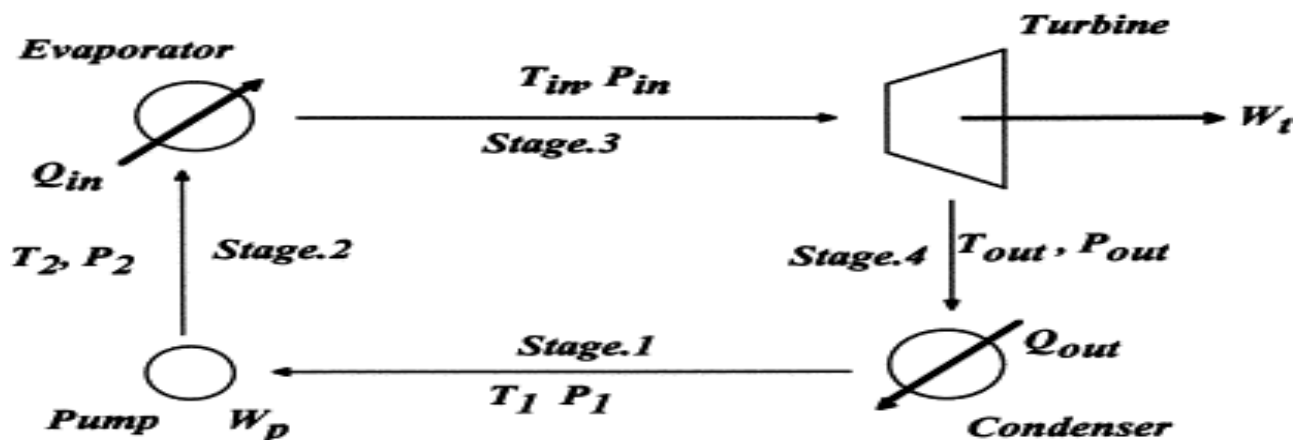


Figure 10-10: Basic Organic Rankine cycle design.

Figure 10-10 shows the main elements of the basic Organic Rankine cycle design. The main elements for design are the evaporator, the turbine/expander, the condenser, and the feed pump. The processes are 1-2 for pumping or compression of working fluid, 2-3 for evaporation of the working fluid, 3-4 is expansion work in the turbine or expander while 4-1 represents condensation in the working fluid condenser.

10.5.3.1. Pre-heaters

Preheaters are used to heat the working fluid to a temperature lower than evaporation point. The preheater is designed such that the power fluid or working fluid flows in the shell and the geothermal fluid flows in the tube side. Baffles guide the flow of the shell side fluid and must be designed for optimum heat transfer. The heat transfer is governed by the equation; $\dot{M}b(h_d - h_e) = \dot{M}w_f(h_2 - h_1)$. In this expression, $\dot{M}b$ refers to Mass flow rate of the brine., h_d is enthalpy of the geothermal fluid at entry and h_e the brine enthalpy at preheater exit. h_2 and h_1 are enthalpies for the working fluid at entry and exit from the preheater[783].

10.5.3.2. Evaporator

The work of the evaporator in the system is to heat the working fluid at the outlet of the feed pump to reach the required turbine inlet thermal conditions. The working fluid is heated to either superheated or saturated vapor state[786]. The evaporator outlet conditions of the working fluid are given by.

$h_{in} = h_2 + (Q_{in}/\dot{m})$ where Q_{in} , the specific enthalpy, h_2 is the enthalpy at evaporator input, and h_{in} is enthalpy at the evaporator outlet [786].

10.5.3.3. Condenser

A condenser is defined as a heat transfer device separating a coolant and the working fluid before it is recirculated [787]. Water or air can be used as the coolant in the condenser. Since an organic fluid has a lower boiling points compared to steam used in the Rankine cycle, air can effectively be used as a coolant. The pressure in the condenser corresponds to the lower pressure of the Rankine cycle, P_1 , while the temperature corresponds to the saturation temperature of the pressure, P_1 . The, Q_{out} , is the condenser load which is the rate of latent heat

rejection the working fluid as it condenses [786]. The condenser heat load can be expressed as $Q_{out} = \dot{m} \cdot (h_4 - h_1)$.

The heat rejected in the condenser is expressed by the equation,

$$\dot{m}(h_4 - h_1) = \dot{M}_{cond} \text{ air } C_{air}(T_{c4} - T_{c1}),$$

Where

$\dot{M}_{cond} \text{ air}$ is air mass flow and

C is the specific heat capacity of air which is acting as the coolant.

10.5.3.4. Feed pumps.

A feed pump is a device ORC power plant used to circulate the working fluid through the evaporator and expander in the system through its pumping or compression mechanism[788]. The feed pump receives saturated fluid from the condenser at low pressure P_1 which is pressurized to P_2 into the evaporator. Work done during circulation W_p is given by the formula.

$W_p = (P_2 - P_1) \dot{m} \rho \eta_p$ [786]. Where $\dot{m}$ is mass flow rate, ρ =working fluid density, and η_p is the feed pump efficiency[786]. Based on the enthalpy of working fluid, feed pump work = $h_2 - h_1$, hence substituting gives.

$$h_2 = h_1 + W_p / \dot{m}.$$

The pump is used to pressurize the working fluid for recirculating in the power cycle. The ORC feed pump ensures a constant supply of the working fluid to the evaporator. It is important to employ appropriate selection charts to control cavitation[192]. Centrifugal pumps are best whenever high discharge volume is needed, but reciprocating pumps are the ultimate choice for high pressure applications[787, 788]. The use of high suction pumps is associated with high incidents of cavitation in pumping systems and should therefore be avoided.

An important parameter in pump selection is the pump work ratio which is defined as the ratio of pumping work to done to power generated[788]. The difference between the gross power and net power output is an important design variable. In some applications, common ratios are 15 to 20% depending on factors like pump design and the working fluid used [789].

10.5.3.5. ORC Turbine.

The most important parameters in turbine design are the, the turbine inlet temperature (TIT), the pressure ratio and the mass flow rate of the working fluid at turbine inlet [786]. For conventional turbines, the TIT is kept high for greater turbine output, but it is not the case for low-grade heat sources and generally, thermal efficiency for low temperature r Rankine cycles is low which need to be overcome. According to [789] superheating at the inlet of the expander causes a reduction in thermal efficiency of the Organic Rankine cycle. From the work by [789] an increase in superheating by 1 °C, reduced the thermal efficiency by 0.021%. As a solution, the organic working fluid selected should have low latent heat but should have high density so that the mass flow rate is kept high at the turbine inlet. [786]. The main challenge is that to operate the system at 0 (zero) superheating value at evaporator exit needs further in evaporator design[789].

Mechanical power is generated when superheated or saturated vapor expands through the turbine to generate mechanical power. The expanding vapor is depressurized by the rotating turbine blades and leaves the turbine at lower pressure P_{out} and at low temperature T_{out} . [790]

The turbine output is given by.

$$W_t = \dot{m} \cdot \eta_t \cdot (h_{in} - h_{out}),$$

where

C_p is isobaric specific heat capacity,

T_{in} is the turbine inlet temperature[786].

Radial flow single stage impulse turbine is proposed in the design since the turbines have better efficiency for low output power plants and are also cost effective.

The selection of an organic Rankine cycle turbine /expander is important as it influences the performance and reliability of the Organic Rankine cycle power system. The selection of the expander type is dependent upon the working fluid and the system size. Not expansion machines can match the selected working conditions mainly in terms of the fluid pressure and flow rate values [789].

10.5.4. Cycle Efficiency

The efficiency of a thermodynamic cycle can be evaluated using parameters like thermal efficiency and the coefficient of performance (COP). The thermal efficiency or cycle efficiency is calculated using the following equation.

$$\eta = (W_t - W_p) / Q_{in} \times 100 \quad [786].$$

Where

W_t is turbine work

Q_{in} is energy input to the system [790]..

10.5.5. Plant Design and Analysis for Different Working Fluids

The objective function in the selection of a working fluid is to maximize the cycle energy and exergy efficiencies while at the same time minimize the total cost of electricity generation at optimized generation output [528, 529]. Therefore, the size of equipment has an important bearing on initial cost of the plant. Cost is a very important factor in the equipment selection as it affects the cost of power and plant profitability. Therefore, a working fluid that will lead to smaller equipment is preferred. The cost of components is estimated [791]. Table 10-15 shows that unit costs for the power plant equipment.

Table 10-15: Cost of ORC equipment [332]

	Component	Unit	Cost (US\$/unit)
1	Preheater	Area (M ²)	450
2	Evaporator	Area (M ²)	500
3	Super heater	Area (M ²)	500
4	Recuperator	Area (M ²)	400
5	Condenser	Area (M ²)	600
6	Feed pump	kW	450
7	Cooling Fan	kW	450

8	Turbine	kW	450

From Table 10-15, it is noted that the condenser is the most expensive equipment per unit surface area at 600 USD/m² followed by the evaporator at 500 USD/m² while the preheaters and fans are the least expensive per kW. The turbine feed pump has same unit cost of 450 USD /kW. The thermal efficiency for both cycles is obtained using the formula below.

Thermal efficiency is given as the ratio of net power to heat energy available i.e.

$$= \frac{W_{net}}{Q_{in}}$$

Net power output of the cycle

Network = Turbine work – pump work – fan work

10.5.6.Assumptions

Assumptions or reasonable scientific guesses are required for successful design of efficient and effective process equipment. The design process used the following assumptions in model development. Table 10-16 shows the summary of design performance targets for the plant equipment.

Table 10-16: Design assumptions[332]

Design parameter	Parameter value
Isentropic efficiency of turbine η_t	0.85
Turbine mechanical efficiency η_{mech}	0.97
Isentropic efficiency of working fluid pump η_p	0.65
Efficiency of fan in the cooling tower η_{fan}	0.65
Efficiency of electric generator η_{gen}	0.7

Table 10-16 shows the target efficiencies for various parts and systems. The turbine mechanical efficiency is assumed to be 97% while its isentropic efficiency is 85%. The pump's isentropic efficiency is 65% while generator efficiency is assumed to be 70%.

10.5.7. Design and Operations Characteristics of the Power Plants

Different geothermal power plants have unique design characteristics because of varying steam properties and overall design considerations. The steam gathering systems for different power plants are not similar, for example Olkaria I and II power plants have one main separator for each well with separator pressure of 6.0 bar-a. On the other hand, Olkaria IV power plant and the new units for Olkaria 1 designated as units 4 and 5 have a common separator set at separator pressure of 12 bar-a. The same applies to Olkaria IV which has separator pressure of 12 bar. The separation pressure for the wellhead power plants is about 15 bar-a. The separator pressure also determines the heat content of separated brine which is reinjected back to the ground.[44, 78, 109, 206, 388, 393] The separated brine properties are summarized in Table 10-17 according to plants.

Table 10-17: Brine mass flows and properties

Plant	Brine (t/hr.) Separation	Press. (bars)	Brine temp. (°C)	Enthalpy of Steam kJ/kg	Total Energy (MJ)/hr
Olkaria I	235	6	158.9	2757	647,895
Olkaria II	566	6	158.9	2757	1,560,462
Olkaria IAU	524	12	188.0	2784	1,458,816
Olkaria IV	815	12	188.0	2784	2,268,960
Wellheads	589	15	198.3	2792	1,644,488
Total energy lost in the brine					7,580,615

From Table 10-17, it is observed that brine from wellhead separators has highest pressure, followed by brine for Olkaria IV and Olkaria I (New unit) from well 4 &5 which is at 12 bars Brine from Olkaria 1 &2 old geothermal power plant have brine leaving separators at 6 bars.

The corresponding brine saturation temperatures show that the used brine has huge extractable energy content. The data also shows that Olkaria IV brine has the highest energy content based on the mass flow rate, temperature, and pressure. The thermodynamic conditions for all the brine in the various power plants studied have potential for further development by installation of binary cycle like organic Rankine cycle power plant extensions to use the waste heat in the brine. Binary technology can be used economically for water dominated geothermal fluids with temperature between 85°C below 170°C.[109, 393, 495, 518].

The total energy lost in the brine for separators leaving Olkaria1, Olkaria II, Olkaria IAU, Olkaria IV and wellheads is 7,580,615 MJ_{th}/hr. This is a huge quantity of energy in waste brine lost that should be extracted with existing efficient technologies. For Olkaria IV field, the brine stream is directed to reinjection well OW-911. This is the brine stream with the largest mass flow at a temperature of 188°C and it receives brine from separators stations SD2 and SD3 in Olkaria IV field. An ORC power plant for installation on this brine stream will be modelled here. This is feasible according to [792].

10.5.8.Power Produced.

The plant was commissioned in September 2014, and it consists of two units each with installed capacity of 149.8MW however the capacity connected to the grid is 140 MW. The generation for Olkaria IV power station between 2015 and 2018 is summarized in Table 10-18.

Table 10-18: Power produced between 2015 and 2017. [332]

Duration	2015-2016	2016-2017	2017-2018
Power generated	525.6 GWh	617.58 GWh	675.5 GWh

Table 10-18 shows that the power generation has increased from 525.6 GWhrs in 2015/2016 to 675.5 GWhrs in 2017/2018 operation years mainly due to improved power plant availability, reliability and efficiency realized over time.

10.5.9. Technology in Use and Plant Description

The Olkaria IV power station operates on single flash geothermal power generation technology. In this cycle, a two-phase liquid from all the production wells is consolidated and sent to the flash tanks or steam separators. There exist four steam separators delivering steam to a common line. The steam is sent to steam scrubbers to remove moisture content in the air then sent to the turbine where it drives the generator. The exhaust steam is then cooled in a condenser before being re-injected as demonstrated in Figure 10-11 illustrating the current design of Olkaria IV flash power plant[332].

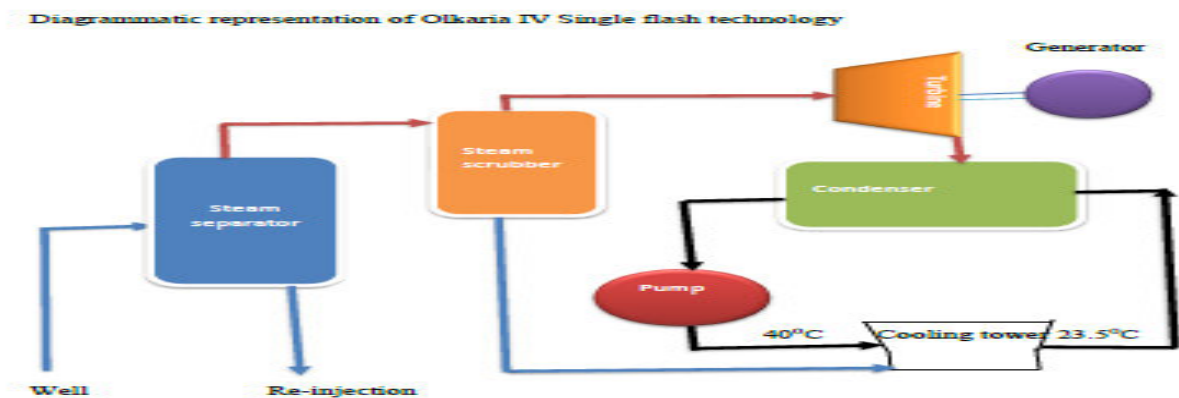


Figure 10-11: Available single flash technology at Olkaria 4 power plant[332]

Figure 10-11 demonstrates the existing flash technology used at Olkaria 4. The main elements of the system are a separator, production wells, reinjection well, steam scrubber, feed pump, cooling tower turbine with electric generator, the condenser, and several accessories.

10.5.10. Comparing the Optimum Operating Conditions.

The optimum operating conditions of a proposed cycle using Nn-pentane and iso-pentane as working fluids are obtained and tabulated in Table 10-19 for comparison. The parameters compared when the two working fluids are used include mass flow rate of cooling air, working

areas for heat exchangers, work done by the turbines and compressors, network done or power generated and working fluid pressure.

Table 10-19: n-Pentane versus isopentane[332]

	Parameter	n-pentane	Iso-pentane
1	Operating pressure (bars)	15	18
2	Mass flow rate of working fluid (kg/s)	119.2	128.4
3	Mass flow rate of cooling air	1264	3176
4	Evaporator area (m ²)	736.7	727.9
5	Condenser area (m ²)	538.4	480.8
6	Preheater area (m ²)	655.4	752.4
7	Pump area (m ²)	969.2	615.5
8	Fan area (m ²)	317.4	795.5
9	Turbine work (kW)	8585.2	7175.9
10	Net work done (kW)	7398.7	5764.9
11	Cycle efficiency (%)	13.9	10.1

Table 10-19 shows that N-pentene generates more power at a higher cycle than Iso-pentane as working fluids. This is also be presented diagrammatically in Figure 10-12

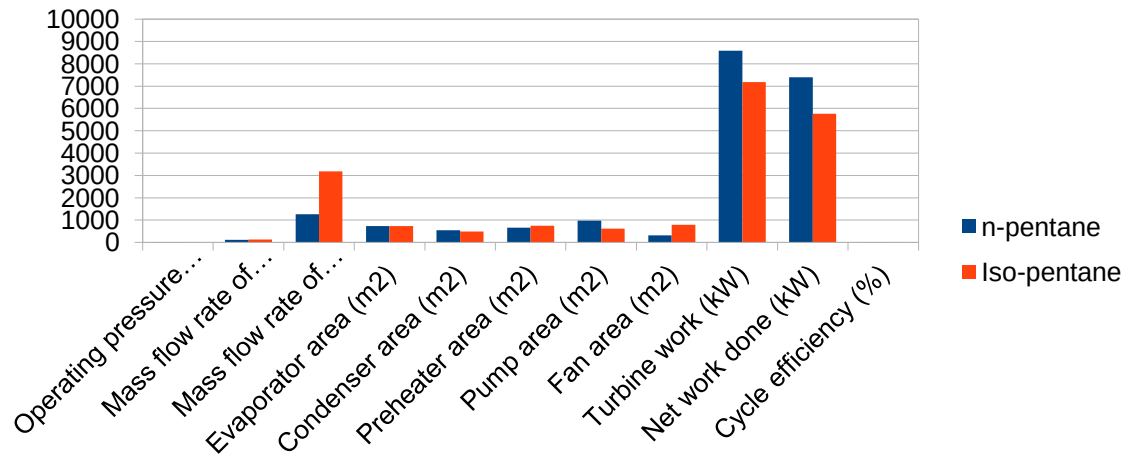


Figure 10-12: Design specifications for n-pentene and iso-pentane as working fluids.

From Figure 10-12, It is noted that n-pentane has a smaller mass flowrate of working fluid, requires a bigger condenser, pump, and fan area, compared to iso-pentane but has higher turbine work and net work done. It requires a small mass flow rate of working fluid hence small equipment like the preheater, fan, evaporator although it requires a larger condenser and evaporator.

10.5.11. Comparing the Cost of Equipment.

The area of the components was established and the cost of equipment for the n-pentane and iso-pentane compared in Table 10-20. All the enthalpies were read from EES software and detailed method of obtaining them shown in the appendix.

Table 10-20: Comparative costs of using iso-pentane or n-pentane [332]

Component	N-pentene			Iso-pentane		
	Size (m ²)	Rate (USD)	Total Cost	Size	Rate (USD)	Total Cost
1 Preheater	655.4 m ²	450	294,930	752.4 m ²	450	338,580
2 Evaporator	736.7 m ²	500	368,350	727.9 m ²	500	363,950

3	Turbine work	8585.2 kW	450	3,863,340	7175.9 kW	450	3,229,155
4	Condenser	538.4 m ²	600	323,040	480.8 m ²	600	288,480
5	Feed pump	969.2 kW	450	436,140	615.5 kW	450	276,975
6	Cooling fan	317.4 kW	450	142,830	795.5 kW	450	357,975
7	Total			5,428,630			4,855,115
8	Net power produced			7398.7			5764.9
9	Specific cost of plant (USD/kW)			733.7			842.2

From Table 10-20, it is noted that although the overall cost of the plant using n-pentane is higher, the specific plant cost in dollars per unit power is lower than the plant using isopentane as the working fluid.

10.5.12. Economic Evaluation of the ORC Plant

In the proposed organic Rankine cycle for Olkaria IV, N-pentane is the working fluid with superior properties based on cost and generation hence efficiency. A cost analysis is based on plant availability factor of 0.5 which is a pessimistic value based on the real value for the year 2017 while the revenue is based on the power purchase agreement rate adopted in March 2019[332]. Table 10-21 is an economic evaluation for the project and estimated payback period.

Table 10-21: Economic evaluation table[332]

Item	Total cost (USD)	Total cost (KES)
Total cost of items	5,275,210	527,521,000
Added project cost	967,300	96,730,000
TOTAL	6,242,510	624,251,000
ANNUAL REVENUE		

Electricity produced in hour	cost of power/hr	Hrs/year	Revenue generated in a year
Revenue	3 cents /kw/hr	8760	97,218,392.4
Pay Back Period Evaluation			
Total cost/revenue generated	627,751,000/97,218,392.4		6.42 = 6 Years 5 months
The plant payback period is 6 years 5 months operating at 50% of the installed capacity			

From Table 10-21, the economic evaluation shows that the payback period for the investment is 6 years and 5 months or 77 months.

The system is a closed loop which limits environmental pollution as and scaling in the turbine which is caused by water. Fouling increases turbine maintenance costs. However, the system faces shortcomings like fouling/scaling effect in the heat exchangers, cavitation, high cost of maintenance and high initial costs of the project compared to the conventional systems[780]. Wider sustainability assessment within the dimensions of energy sustainability, i.e. technical, social, institutional, environmental, and economic sustainability should be done to increase the project socio-economic value so that the project can be more sustainable[140, 141, 758, 793, 794].

10.5.13. Fouling/Scaling Effect

The chemistry of the geothermal fluid has significant concentrations of minerals and gases which can cause scaling and corrosion of the installations which the geothermal fluids flow through [795]. Geothermal resources have a very high mineral content dissolved in water to form brine. Some of the minerals contained in the geothermal fluid include magnesium, potassium, calcium, and sodium with actual composition varying from one geothermal field to another. The chemistry of the geothermal fluid varies mainly according to temperature, but generally the fluid is dilute for low-temperature fields [78, 795]. However, upon flashing, the concentration of the minerals increases to a higher level hence the risk of fouling or scaling.

Careful material selection is very important in original design of geothermal plants for long and reliable service[796]. However, geothermal fluids are in most cases not corrosive and hence the main casing and pipe material selection is using mild steel. Experience has however shown many cases of manageable localized corrosion challenges in many geothermal installations, which require proper material selection, as well as good engineering practices operation and maintenance. The condensate is corrosive and hence stainless-steel pipes or fiberglass are required. Due to the presence of H_2S , Copper material is not recommended. There is additional requirements to for the air control room to filter H_2S from in the ambient air to protect the copper wiring and switchgears[78, 795, 797]. The use of surface-active inhibitors to prevent the formation of deposits and erosion–corrosion processes is another measure that can enhance corrosion and scaling control in geothermal power plans and can be considered in the detailed design phase[798].

10.5.14. Cavitation in the ORC Turbines/expanders and Pumps

Cavitation is a phenomenon that occurs when part of liquid suffers encounters vaporization when the absolute pressure in a local fluid field is reduced to saturated vapor pressure [799]. Cavitation is common in Organic Rankine cycles due to the low boiling temperature of most organic fluids. Cavitation occurs in pumps, turbines, and other rotating machines. The main cause of cavitation is dynamic variations of pressures and temperatures in the fluid system. In a pump, it occurs in the suction stage when pressure in the liquid is instantaneously reduced to or close to the fluid saturation pressure that corresponds to the liquid temperature[800, 801]. Cavitation in pumps degrades performance, causes noise, vibration, and mechanical damage. Cavitation can be reduced in pumps by providing adequate net positive suction head (NPSH), or net positive suction head available (NPSHa). This is the total energy of a fluid at the inlet of the pump less saturated vapor pressure at the operating temperature [799].

10.5.15. Cooling for Organic Rankine Cycle

Power plants have high cooling water requirements and account for significant number of freshwater requirements. For example, about 41% of US fresh water consumption goes to cooling in power plants, of which 90% is employed in condenser cooling[802]. A simple and low-cost water-to-steam is historically applied for condensers and account for about 43% of the US power plant cooling systems[803].

It is necessary to cool the turbine or expander exhaust fluid before recirculation. This is usually done in condensers. An ideal coolant is needed to extract heat to desired temperature before recirculation usually by use of air or water. Air has lower heat transfer which leads to a larger heat transfer areas and volumetric flows compared to water[803, 804]. If water is used as a coolant for the Organic Rankine cycle, a shell and tube heat exchanger is preferred since it offers greater flexibility in design, and they are ideal for some liquid coolants. If air is the coolant used then a cross-flow finned tube heat exchanger is the preferred choice because it has high heat transfer area densities thus reduces the mass and volume flow rate requirements[804]. Since water has got higher heat transfer area, its use as the coolant reduces the size of the heat exchanger. The finned tube condenser can be made of aluminum [803, 804].

10.5.16. Non-Condensable Gases

Non condensable gases (NCGs) are gases which cannot be condensed in normal operation. These gases include ordinary air and nitrogen. Non condensable gases exist in four mains. Firstly, can permeate the system through poorly sealed pipes and valves. The second method is through generation from the decomposition of the working fluids at temperature and action of corrosion of devices during operation[805]. Thirdly, some non-condensable remain in the system after vacuum-pumping. Finally, non-condensable gases may infiltrate the organic Rankine cycle during repair and replacement of components. With application of, silicone oils as favorably choice for high temperature applications, the ORC system can be troubled due to low saturation pressure of silicone oils at room temperature[806].

Since non condensable gases in the Organic Rankine cycle have a negative impact operation, maintenance, and output, they should be control through proper operation, maintenance, selection of the correct working fluids and provision for removal of the gases from the system through well designed and located venting outlets. The cycle operating conditions should also be monitored and well designed to limit entry and generation of non-condensable gases[332].

10.5.17. Results and Discussion

This study showed that it is technically and economically feasible to generate extra power and increase thermal and overall efficiencies of an already developed flash power plant by using an Organic Rankine cycle (ORC) without drilling additional production wells or increasing

steam demand. This will increase generation and electricity revenue. Most geothermal power plants globally use the single flash technology to produce electricity which generates significant quantities of low temperature waste brine. Generation will significantly be increased by using organic Rankine plant as a bottoming plant to a conventional geothermal plant by increasing output and efficiency of electricity generation. This study demonstrated that it is both technically and economically viable to generate extra power from used brine from a single flash geothermal power plant and a detailed design and evaluation should be done to determine actual costs and returns on investment[332].

10.5.18. Summary of Results

Binary thermodynamic cycles are effective energy conversion cycles for low and medium temperature fluids generally between 100 °C and 150°C. Established binary cycles for low temperature geothermal are Kalina cycle (KC), organic Rankine cycle (ORC), and Goswami cycle (GWC) which can be designed and presented in different formats. Selection of a working fluid is a very important exercise in the design of a binary cycle. Selection of the best fluid should be guided by the understanding that the thermodynamic performance of ORCs is a function of critical temperature of fluids[332].

A cycle realizes maximum cycle efficiency when the turbine inlet pressure is close to the critical pressure. However, this is not the same for all working fluids since fluids like R115, R143a, and propylene which can achieve maximum efficiency at a highly supercritical turbine inlet pressure with temperature of just 66–69% of the maximum heat source temperature[807].

The extraction of waste heat from the geo-fluid exiting a flash cycle is extremely significant from the economical as well as environmental point of view. The Single flash Olkaria 4 power plant at Olkaria in Naivasha in Kenya has the potential to generate extra power through a binary cycle power based on the high enthalpy of brine leaving the flash station at a pressure of 12 bars and saturation temperature of 188°C, hence energy loss of 2,268,960 MJ_{th}/hr based on the enthalpy of saturated steam at 12 bars. This study also revealed that the total energy wasted from the Olkaria stations through used brine leaving flashing stations is significant. It is estimated that the geothermal fluid leaving the flashing stations for Olkaria1, Olkaria II, Olkaria IAU, Olkaria IV and wellheads is about 7,580,615 MJ_{th}/hr which is quite high in terms of lost clean power generation. This energy can generate electricity hence more revenue while

at the same time mitigating against greenhouse gas emissions through avoided generation from fossil fuel sources. [332].

The selection of the most appropriate working fluid is based on several technical, thermodynamic, and economic considerations. A working fluid affects the design and performance of the organic Rankine systems since it affects its design, cost, and performance. [789, 808].

There is a relationship between maximum achievable exergy efficiency and the critical temperature for both pure working fluids and mixtures of working fluids. Working fluids with the highest efficiency have a critical temperature in the range 80–84% of the maximum temperature of the heat source. Additionally, a cycle realizes maximum cycle efficiency when the turbine inlet pressure is close to the critical pressure. However, this is not the same for all working fluids since fluids like R115, R143a, and propylene realize maximum efficiency at a highly supercritical turbine inlet pressure with temperature of just 66–69% of the maximum heat source temperature. The factors to consider are summarized in Table 10-22.

Table 10-22: Summary of selection criteria for working fluids[332]

Criteria	Approach
1 Price:	The price of the Organic fluids used affects the overall cost and preference should be fluids that have wider industrial applications which are generally cheaper.
2 Density of organic fluids	Generally, high density fluids are preferred to low density fluids. Low density fluids require a higher volumetric flow rate which implies bigger size components which increases installation cost. There is however need for a tradeoff since high volumetric flow rate facilitate reduction of rotational speed of the expander which improves expander reliability.
3 Condensation pressure	The condenser should have a pressure as close as possible to the atmospheric pressure. This is because high condensation pressure technically increases system pressure which increases design cost. Too low pressure increases sealing needs and increases the size of the

	condenser.	
4	Freezing point	Freezing point should be below the minimum ambient temperature to avoid solidification of the working fluid especially during idle periods
5	Cycle top pressure	The top cycle pressure should be below the fluid critical pressure to prevent liquid droplets formation during expansion process and overcome instability during vaporization. This also reduces system costs in terms of design, operation, and maintenance costs. A trade-off must be found through a techno-economic analysis
6	Heat transfer coefficient	High heat transfer coefficient reduces surface area requirements hence the size of the installation as well as cost.
7	Decomposition temperature	The system and environmental temperatures should be lower than decomposition temperatures of the working fluids.
8	Molecular weight:	Working fluids with high molecular weight require less rotational speed of expanders which reduces generator cost.

From Table 10-22, it is noted that at least eight factors are considered in the selection of the working fluid. They include molecular weight, heat transfer coefficient, fluid decomposition temperature, cycle top and condensation pressures, density, and price which is a combination of technical and economic factors.

The main elements and systems of an organic Rankine cycle which must be designed and optimized are the pump and pumping system, the evaporator, the generator, the expander, and the condenser which are summarized in Figure 10-13 as an assembly.

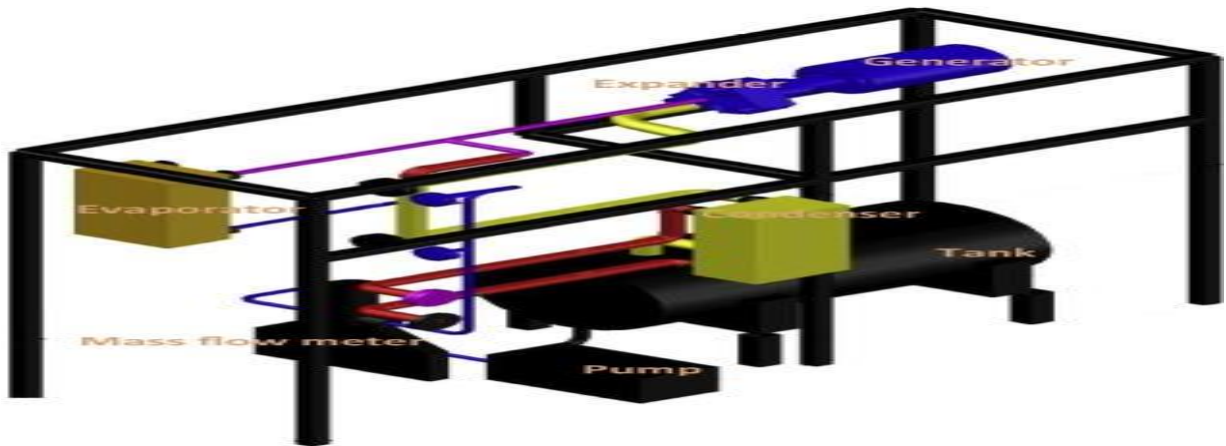


Figure 10-13: Assembly of the Organic Rankine cycle

Figure 10-13 shows the relational arrangement of the main elements and systems of an organic Rankine cycle which are interconnected by pipes and the working fluid.

10.5.19. Design Strength and Weaknesses

10.5.19.1. Design Strength

This study proposed a relatively efficient thermodynamic cycle compared to the conventional Rankine cycle which uses water as the working fluid. The organic Rankine cycle (ORC) is considered to be an effective strategy in low grade heat recovery with wide applications in heat recovery from sources like biomass combustion, industrial waste heat, and geothermal heat which helps in mitigating environmental greenhouse gas emissions and the related threat of global warming[332, 809]. Besides the environmental benefits, waste heat and low grade heat recovery which prevents fuel wastage, creates more revenue from extra power sales and improved system efficiency and profitability[3, 21]. According to [810] the integration of an optimized, well-designed Organic Rankine cycle can effectively increase overall cycle efficiency and cut down on emissions cost effectively with fuel savings with about 2–5 years payback

The study estimated lost energy in the used brine for targeted flash systems to be about 7,580,615 MJth/hr. This is huge quantity of energy lost that can be recovered for extra power generation and earn extra revenue for the investors while contributing towards the global energy transition by generating power from renewable and waste energy resources of about

7.4 MWe. The project proved to be technically and economically feasible with a payback period of about 77 months using n-pentane as the working fluid. More accurate project data can be subjected to a detailed design and analysis and economic evaluation.

10.5.19.2. Design Weaknesses

An efficient and effective Organic Rankine Cycle is a function of the working fluid used and the expander or turbine design applied by the system which determines the cycle efficiency and power out [809]. The selection of the fluid was not thoroughly done given that only two working fluids were compared. The important performance parameters like the degree of superheat was not established and analyzed to determine the appropriateness of selected working fluids for the design[789].

Additionally, the difference between gross power output and net power output of the design, i.e. the back work ratio was not considered in the design. and can be mentioned as a function of pump performance. The back ratio is the ratio of pumping power used to the power generated[789]. Therefore, a more detailed design analysis and selection of the most efficient and cost-effective pumping system is recommended in the detailed design of the heat recovery system[332].

The organic Rankine cycle has got challenges in low grade and waste heat recovery because of the relatively low energy conversion efficiency which is generally between 8–12%. Other competing cycles which may yield higher efficiency based on the cycle design are Supercritical Rankine Cycle (SRC), Kalina cycle (KC) and Trilateral Flash Cycle (TFC)[809]. The project can yield more power if more efficient conversion cycles are adopted instead of the organic Rankine cycle which was used in this study[332].

10.5.20. Conclusion

It is both economical and technically feasible to generate electricity from low-temperature heat sources generally 80–300 °C like geothermal, waste heat, solar, biomass, cooling water, etc. The Organic Rankine Cycle (ORC) as applies organic working fluids get higher efficiency than flash steam power cycles .

This study showed that brine leaving a single flash geothermal power plant has significant quantities of recoverable energy for extra power generation using binary thermodynamic

cycles. Various binary cycles and working fluids can be used based on the condition of the geothermal fluid mainly in the form of fluid temperature. Different working fluids have differences in performance characteristics, making selection of an organic fluid a very important function in the design of an organic Rankine system. Comparison between, Isopentane and n-pentane similarly exhibited differences in properties with n-pentene exhibiting superior performance in terms of power plant thermal efficiency and power output, but research on use of mixtures of organic working fluids tend to yield attractive results in terms of cycle performance. Technical evaluation of converting flash geothermal power plants shows that the investment is technically viable while projected economic performance proved that the showed that the proposed plant is economically viable. Overall, the power plant efficiency will improve, revenue will increase, and extra green power means reduced carbon emissions and sustainability in power generation through fossil fuel substitution in power generation from renewable, low carbon and reliable geothermal power generation.

Therefore, the ORC is ideal for low-grade heat recovery, but optimum performance requires a careful selection of the working fluid based on the thermodynamic conditions of the heat source, required exit temperature and the expected work output within existing budget outlay.

10.5.21. Recommendations

This study concentrated on Olkaria 4 flash power plant out of the several geothermal flash power plants at Olkaria in Kenya, namely Olkaria I, Olkaria II and the several wellhead power stations operated by the Kenya Electricity Generating Company (KenGen). while noting that Olkaria II which is privately owned operates a binary cycle power plant of capacity 139 MW[811]. Similar studies are recommended for all other flash power plants and the wellhead power plants to identify the potential of developing flash-binary electricity generation and increase the generation capacity from geothermal fields. Since the organic Rankine cycles is more efficient, future geothermal power plants should consider using more efficient cycles like the binary cycles as opposed to the less efficient flash steam power plants.

CHAPTER 11:

SUSTAINABILITY MEASURES FOR FOSSIL FUEL ENERGY AND POWER PLANTS

11. Waste Plastics to Oil

11.1. Overview

This section summarizes work published references [100, 320] authored by the candidate on waste plastics to oil as a waste to energy pathway. It was noted in these studies that since plastics are cheap, lightweight, and durable and can easily be molded to many different products, shapes, and sizes, they are widely used globally leading to their increased production and use. The manufacture and consumption of plastics has been growing since their first production in 1950s. About 4% of global oil and gas production is used as a feedstock for plastics and 3–4% used to provide energy for their manufacture. Plastics have a wide range of applications because they are versatile and relatively cheap. This study presents an in-depth analysis of plastic solid waste (PSW). Plastic wastes can be technically used for oil production because the calorific value of the plastics is quite comparable to that of oil making this option an attractive alternative. Oil can be produced from plastic wastes by thermal degradation and catalytic degradation, while gasification can be used to produce syngas.

11.2. Introduction

The world is currently faced with the twin challenge of fossil fuel depletion and strict emission requirements because of global concern over emissions and global warming leading to the emission targets set at the Paris agreement[100]. Extraction of oil from waste plastics has attracted the attention of industry and academia as a feasible measure to mitigate the challenge of fossil fuel depletion, clean environment, global growing demand for fossil fuels[101, 391, 812]. The global plastic production has continuously grown despite the fact that recycling rates are comparatively low, with just about 15% of the 400 million tonnes of plastic currently produced annually being recycled. The rate of global plastic production and use has been growing fast than recycling rates over the last 30 years, which implies that more and more plastic wastes are released to the environment. The global production of plastics is forecast to triple by 2050 and is expected to account for a fifth of global oil consumption[813]. Through pyrolysis, a

combustible liquid fuel can be produced from waste plastics [814]. These plastics are expected to reach increase to around 12 billion tonnes by the year 2050[815]. The industrial scale production of plastics started in 1940s and 1950s with demand and production growing steadily over time. In 2013, about 299 million tons of plastics were produced globally[816]. The production increased to more than 322 million tonnes per annum in 2015[817]. The global production of plastics is currently over 400 million tons per annum[818, 819].

The use of plastics generates significant quantities of waste plastics currently contaminate the waterways, aquifers and limits the landfill areas. Over 14 million tons of plastics are annually dumped and as a result, they cause the death of 1,000,000 species of aquatic life [820]. Common options for plastic waste disposal include feedstock recycling, mechanical recycling, energy recovery, incineration as municipal solid waste. Incineration of plastics releases noxious odors, harmful gases, dioxins, HBr, polybrominated diphenyl ethers and other hydrocarbon based on composition[818]. About 15 million tons of these plastics reach seas and oceans annually, U.S. emissions from plastic incineration reached 5.9 million metric tons of carbon dioxide in 2015 and will reach about 49 million metric tons by 2030 and 91 million metric tons by 2050. In the past, the United States and other Western countries used to send contaminated waste to China, thus moving responsibility of waste management to China[819]. However, in 2018 China stopped importation of the wastes from western countries [1].

The market globally is dominated by thermoplastic types of polypropylene (PP) at about 21%, low density polyethylene(LDPE) and linear low-density polyethylene (LLDPE) with about (18%), polyvinyl chloride (PVC) with a market share of 17%) and high-density polyethylene, (HDPE) with 15%. Others with high demand are polystyrene (PS), and expandable PS with (8%), polyethylene terephthalate (PET) with 7%, excluding PET fibre and the thermosetting plastic polyurethane . The main challenge with plastic products is that about 40% have a short service life f less than one month[816]. Plastics have a wide range of applications like Plastic making synthetic fibres, foams, adhesives, coatings and sealants. In Europe, 38% of plastics are used in packaging 38%, 21% are used in building industry, automotive industry uses about 7%, electrical and electronic applications account for 6%, while other sectors account for 28% of plastic consumption like medical and leisure[206, 816].

It has been concluded that waste plastic fuel has similar properties to diesel fuel and can be used as a substitute for diesel[819, 821]. The removal and disposal of huge plastic wastes is a global concern with economic and environmental implications mainly because of population growth, industrialization and attractive properties of plastic materials[822]. The current rate of economic development and growth won't be sustainable without sustainable and controlled consumption rates of fossil fuel sources of energy[823]. The demand for fossil fuels in power generation, transport, industrial and domestic applications continues to grow globally while fossil fuel reserves face imminent depletion[824]. The growing population and demand for industrial products and hence packing materials has also seen increased use and disposal of plastics as solid wastes[825]. As solid, wastes, plastics are undesirable because they are non-biodegradable[824]. The main advantage of plastics and hence their increasing use is that they are cheap, quick to produce, easy to design and fabricate, are durable, nonperishable and recyclable[824, 825]. Synthetic plastic production is about 400 million tons of which about 50% ends up in landfills, while about 15 million tons of the plastics end up in oceans and seas annually [819]. Global plastic production accounts for about 8% of world oil production[826]. Over one trillion plastic bags are produced annually making them important end user plastic product globally[827, 828]. Common forms of plastic wastes include single user plastics in the form of drink bottles, wet wipes, cotton bud sticks, sanitary items and which are often disposed of by incineration and landfilling[819].

11.3. Plastic Production

Plastics are synthetic organic polymers, manufactured from petrochemical materials. The first plastic was invented in the early 1900s, with the type and quantities drastically increasing later for different applications. Plastic management is serious concern today because increased use of plastics has led to waste disposal challenges as more than 300 metric tons are currently produced per year. In the European Union, about 25% of plastic wastes are recycled as recycling faces challenges like low quality of the recovered and recycled material and products[829]. Between the year 1950 and 2015, some 8,300 million tons (Mt) of plastics were manufactured globally of which 6,300 million tonnes representing 9% were recycled, 12% were incinerated and 79% were land filled [6]. The annual global production of plastics has reached 400 million tons in the year 2020 [9,10]. The production grew by 3.4% between 2014 and 2015. Analysis of annual plastic

demand shows a compound annual growth rate (CAGR) of 8.6% between 1950 and 2015 [830, 831].

A significant portion of these plastics end up in oceans and seas where they disintegrate into micro-plastics and nano-plastics. These chemical products are consumed by aquatic animals causing a negative impact on zooplankton in terms of population and mortality [814]. shows the growth in global plastics production between 1950 and 2020.

Table 11-1: Global plastic production between 1950 and 2020[830, 831].

	Year	Production (million tons)
1	2020	400
2	2015	322
3	2014	311
4	2013	299
5	2011	280
6	2009	250
7	2002	200
8	1989	100
9	1977	50
10	1950	1.5

This is diagrammatically presented in Figure 11-11.

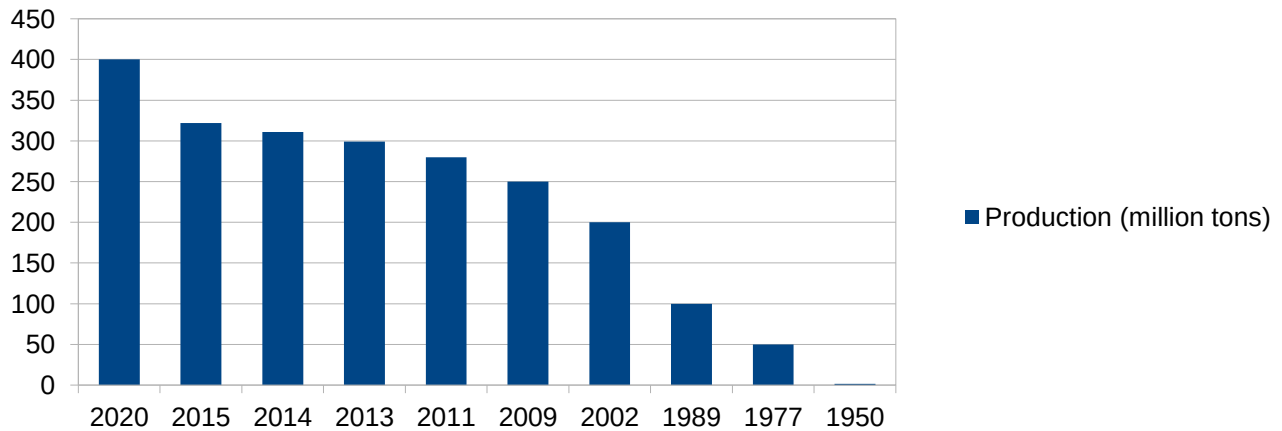


Figure 11-1: Global plastic production between 1950 and 2020

From Figure 11-11 and Table 11-1, it is noted that global plastic production was about 1.5 million tons in 1950 and about 400 million tons in 2020. This represents a growth of about 266% in global plastic production between the year 1950 and 2020.

11.4. Plastic Disposal and Recycling

To attain the best environmental outcome, a hierarchy of measures is proposed in waste prevention and management[832]. The measures are waste prevention, waste reuse, and waste recycling. Plastic waste recycling which can mechanical or feedstock recycling, energy recovery and final waste disposal. End-of-Life treatments for plastic wastes include mechanical recycling like reprocessing for production of new products. Plastic recycling transforms the materials to smaller molecules which can be used for manufacture of new petrochemicals and polymers[114, 831]. Energy recovery techniques include combustion of plastic waste for production of heat, steam, and electricity. Combustion of plastics is a convenient energy sources because of their high energy content. Landfilling is the end-of-life treatments in the hierarchy of plastic waste management [821, 831].

Environmental challenges of plastic wastes can be best addressed through recycling. There are four major types of recycling that can be applied to plastic wastes. These are primary, secondary, tertiary, and quaternary recycling. Through chemical recycling, plastics can be used as feedstock or fuel which reduces the net cost of disposal besides producing useful energy. Plastics can also be converted into basic petrochemicals which take the form of hydrocarbon for several process and energy applications [3]. Oil can be processed from waste plastics through thermal degradation, gasification and catalytic cracking, [823]. The main challenge facing plastic

recycling is lack of incentives and proper systems for waste collection and separation[821, 833]. Recycling reduces quantity of waste left available for landfilling and indiscriminate disposal in the environment. Socially, plastic recycling creates jobs and adds value to the gross domestic product of a country[834].

In Japan, the Sapporo plastic Recycling plant (SPR) was established in the year 2000 for commercial liquefaction in Japan through plastic pyrolysis with recycling capacity of 50 tons/day [835]. Through its cascade facility, the plant mixes plastics from municipal solid waste stream with waste from other recycling processes in the ratio 40% to 50% of the total feedstock material. Another important innovation from the recycling is that they have learnt to deal with the benzoic acid by converting it to benzene with little or no effect to the fuel potential. Lessons from this plant show that pyrolysis can be done for residues with high PET and PVC content can be blended with municipal solid waste plastic stream at up to 40wt% with little or no effect to the reactor as well as the product quality [823, 835].

The main products of plastic pyrolysis are light oil, medium oil, heavy oil, and sludge. The common applications of pyrolysis products are solid fuel, cogeneration oil, engine fuel and raw material for further processing to produce plastics and other products.

There are six essential steps in waste plastic recycling. They are.

- i.) Plastic waste collections.
- ii.) Categorization of plastics wastes by sorting.
- iii.) Cleaning to remove impurities by processes like washing.
- iv.) Waste shredding and resizing of cleaned plastic waste.
- v.) Identification and separation of the wastes
- vi.) Compounding of plastic wastes[836]

11.5. Methods of Plastic to Oil Conversion

There is growing importance of plastic to fuel conversion due to increasing awareness and evidence of environmental degradation caused by plastic wastes. Especially the single use plastics amidst people's limited recycling habits [837]. It is estimated that less than 5% manufactured plastics are recycled yet production is projected to increase 3.8% annually until the year 2030, with about 6.3 billion tonnes having been produced since plastics production started

over 60 years ago. A significant fraction of these plastics ends up in seas and oceans posing disruption of marine environment. It is estimated that these plastics can take a minimum of 450 years to biodegrade. Economically, it is estimated that plastic to fuel investment will create about 39,000 jobs and about \$9bn in economic output. [837]. Plastics can be converted to fuel in form of hydrogen, crude oil, diesel, and sulphur.

11.5.1. Plastic to Hydrogen Fuel

Hydrogen is normally produced commercially by catalytic steam reforming of natural gas, naphtha, and hydrocarbons. There is growing interest in alternative feedstock for hydrogen production mainly because of concerns over security of supply and price instability. Hydrogen can be produced from plastics especially the polyolefins [838]. As a major development in the waste plastic to fuel, researchers from Swansea University were able to convert plastic waste into hydrogen fuel by addition of a light-absorbing photo catalyst to plastic material for absorption of sunlight which then transforms it to chemical energy in the process of 'photo reforming. In this process, the plastic and catalyst mixture put in alkaline solution and exposed to sunlight, which leads to chemical breakdown and production of hydrogen gas[837]. At Oxford's department of chemistry, particles of mechanically pulverised plastic were mixed with a microwave-susceptor catalyst of iron oxide and aluminium oxide and subjected to microwave treatment which produced a large volume of hydrogen while a carbonaceous residue material formed was mainly carbon nanotubes. This proved that 97% of hydrogen in plastic can be recovered in a short time period directly with no carbon dioxide emission[815].

In the study by[839], hydrogen gas was produced from polyethylene waste via a two-stage pyrolysis–low-temperature plasma catalytic steam reforming process carried out at about 250 °C. This produced pyrolysis gas that were catalytically steam-reformed in the presence of low-temperature non-thermal plasma in form of dielectric barrier discharge to produce hydrogen gas. Hydrogen yield was increased in absence of a catalyst by increasing the plasma power. Various catalysts that can be used in hydrogen production include Ni/Al₂O₃, Fe/Al₂O₃, Co/Al₂O₃, and Cu/Al₂O₃. Tests showed that Ni/Al₂O₃ catalyst resulted in the highest yield of hydrogen at 1.5 mmol/g of plastic used. Investigation on the impact of steam addition to the plasma catalytic process at different steam weight hourly space velocities (WHSVs) with Ni/Al₂O₃ as the catalyst showed that steam to promotes catalytic steam reforming reactions leading to more hydrogen

production. The highest yield realised was 4.56 mmol/gram of plastic at a WHSV of 4 g h⁻¹ g⁻¹ catalyst[839]. Therefore, plastics to hydrogen fuel conversion is a feasible process and hence a promising plastic to green energy pathway.

11.5.2. Plastic to Diesel

In this conversion, plastics are broken down with heat and/or reactive, toxic chemicals, which results into the breaking of the plastic material bonds. This process can produce a liquid fuel that can be used to run engines for transport and industrial applications. The catalysts selected have to be compatible with various types of polyolefin additives so that plastic wastes can be processed without pre-treatment making it easier and cheaper[840].

11.5.3. Plastic to Crude Oil

Plastics have successfully been converted to crude oil by pyrolysis of high-density polyethylene bags. The plastic crude oil produced be refined by fractional distillation to produce gasoline and two different types of diesel[840]. By adding antioxidants, the oil product made is superior to conventional diesel fuels in terms of parameters like lubricity and derived cetane number, which is a measure of combustion quality of a diesel fuel[837].

11.5.4. Plastic to Sulphur

Waste plastics can be converted to sulphur fuel by using the discarded material as feedstock [840]. This technique is however still under research and development with main concern being application of sulphur as a fuel when the main environmental concern is to limit sulphur dioxide emissions[100].

11.6. Plastic Pyrolysis

Pyrolysis is a complex series of reactions that are both chemical and thermal that depolymerize an organic material in the absence of oxygen[841]. The process requires the heating of plastics to high temperature and then the volatile material is distilled or separated for reuse as energy material[840]. In waste plastic pyrolysis, the plastic waste material is subjected to high temperatures in absence of oxygen and presence of a catalyst to help in the gentle cracking of long chains. The gases produced are condensed in the condenser to yield low Sulphur content distilled waste plastic oil[824, 825]. The use of catalysts prevents the formation of dioxins and

Furans (benzene ring) during the process[824]. Thermal degradation of plastics decomposes plastics three main fractions namely: gas, crude oil, and solid residue. The crude oil consists of the higher boiling point hydrocarbons from non-catalytic pyrolysis process. Efficient production of gasoline and diesel from plastic wastes requires optimization of parameters like catalysts used, pyrolysis temperature, and plastic to catalyst ratios. The quality of crude oil can be improved by co-pyrolysis of plastics with coal or shale oil which reduces the viscosity of crude oil produced[842]. Processes used in the conversion of plastics to fuels include gasification, pyrolysis, plasma process and incineration. In pyrolysis, plastic wastes are converted into solid, liquid, or gaseous fuels by thermal degradation of long polymer chains into shorter and simple molecules in the absence of oxygen. The main products of pyrolysis are combustible gas with high calorific, combustible oils and carbonized char[827].

Pyrolysis refers to the process of converting plastics into solid, liquid, or gaseous fuels by through thermal degradation of long chain polymers into less complex molecules in the absence of oxygen. The products of pyrolysis include high calorific gas, high quality oils and carbonized char. Pyrolysis can produce as high as 80wt% at moderate and requires temperatures of 300 -900 °C [843, 844]. The main processes are slow, fast, flash and catalytic plastic pyrolysis[821, 845]. The various types of pyrolysis are conventional pyrolysis (slow pyrolysis) which proceeds under a low heating rate with solid, liquid, and gaseous products in significant portions. It is an ancient process used mainly for charcoal production[821, 845]. Vapours can be continuously removed as they are formed; fast pyrolysis, which is associated with tar, at lower temperature (850–1250 K) and/or gas at high temperature (1050–1300 K). Others are thermal and catalytic pyrolysis[685, 827]. Fast or flash pyrolysis is the most preferred technology, and it takes place at high temperatures and short residence time. Fast pyrolysis is also called thermolysis and involves rapid heating of a carbonaceous material to high temperatures in the absence of oxygen.

Pyrolysis technology has been improved over the years to produce valuable liquid oils from by valorisation of organic materials. The process still faces challenges that arise from the use of the different feedstock types. Critical to success of pyrolysis is to design new reactor types over to optimize product yields while at the same time minimizing energy consumption and process costs. Pyrolysis is a mature technology with several commercial plants in operation for biomass and plastic feedstock. Pyrolysis can effectively be used to treat various plastic wastes ranging from packaging waste to more complex plastic materials like rubber and WEEE (waste electrical

and electronic equipment), ELV (end of life vehicle) and hospital waste that are often contaminated with toxic and hazardous substances. Products of plastic pyrolysis are pyrolysis oil, a hydrocarbon rich gas, with heating value of 25–45 MJ/kg which makes it ideal for process energy recovery and char. Hence the pyrolysis gas can be fed back to the process to extract the energy for the process heating purpose which substantially reduces the reliance on external heating sources[836]. Figure 11-2 demonstrates a pyrolysis process with inputs and product outputs.

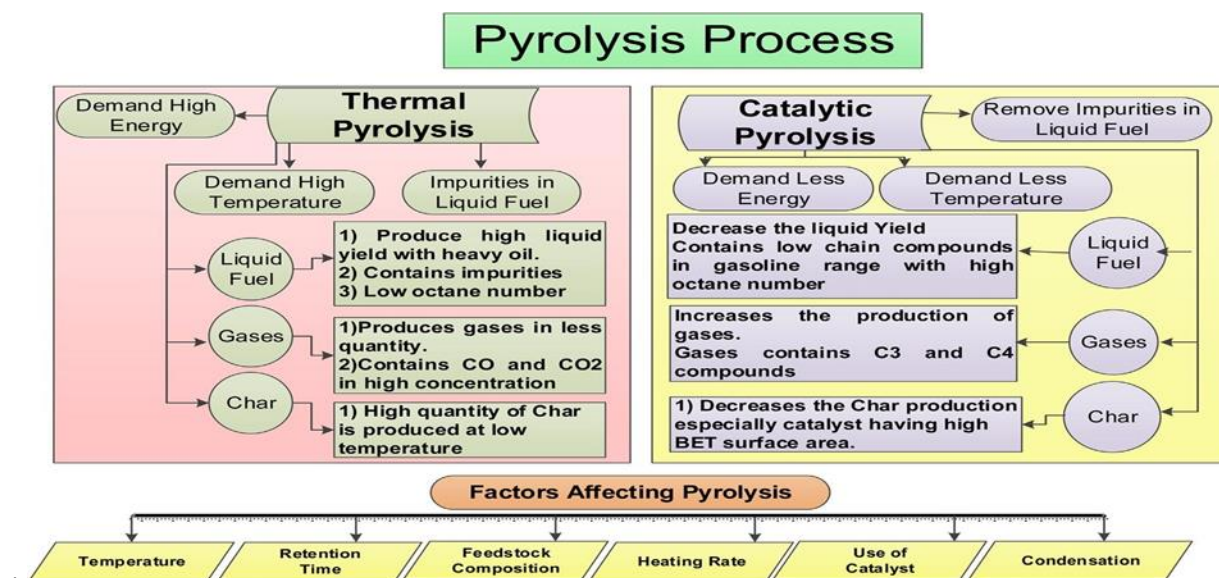


Figure 11-2: Industrial waste plastic to oil pyrolysis plant [812, 846]

Figure 11-2 shows the main elements of the plastic pyrolysis process, namely feed preparation chamber, the reactor, char collector, fuel storage tank and the cyclone.

The waste plastics are mixed and heated in the absence of oxygen in a process called cracking which leads to production of a gas. The gas or vapor is distilled into products ranging from heavy wax and oils to light oils and gas. Most of these products have a potential to provide new building blocks for new polymers or can instead be used as fuel[813]. Figure 11.3. demonstrates the plastic pyrolysis process.

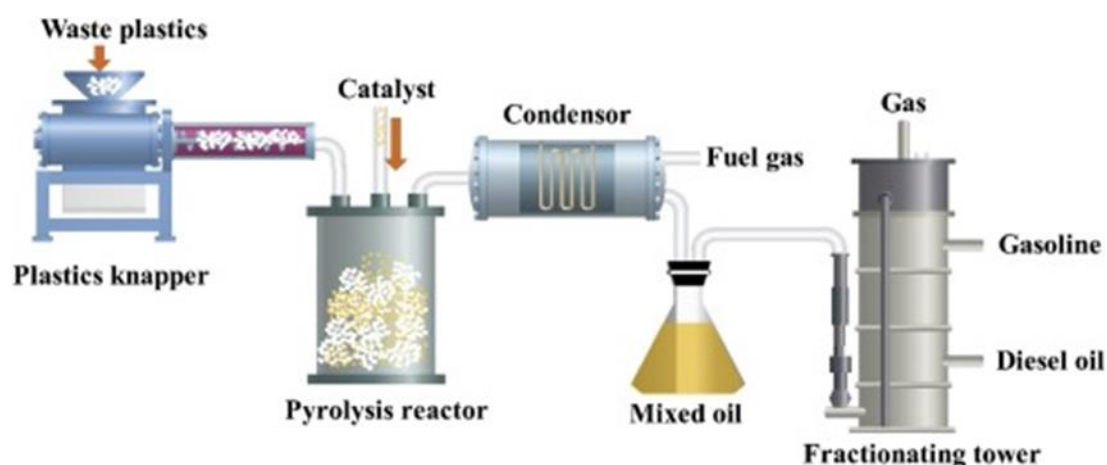


Figure 11-3: Plastic pyrolysis process description [813]

From Figure 11-3, it is noted that the main elements of a plastic pyrolysis process plant are the reactor, condenser, fractionating tower, and condenser.

A pyrolysis plant can recycle even the hard to recycle plastics like polystyrene and flexible packaging into 75% liquid oil. Which can be used as sustainable fuel and plastic manufacture feedstock. The remaining 25% can be used as a wax equivalent for manufacture of candles and paint, while the produced gas and char can be used as energy sources for the plant[813]. The most common technology used in plastic waste disposal is thermal treatment which generates heat for either process heating applications or steam generation and power production[847]. The process starts by feeding a cylindrical chamber where heating is done. In thermal pyrolysis, plastics are heated in inert conditions to decompose organic parts to liquid and gaseous fuels. However, thermal pyrolysis results in lower quality fuels due to high temperatures as the products have lower molecular weight [848]. The generated pyrolytic gases are condensed in a condenser system, to produce a hydrocarbon distillate. The distillate comprises of straight and branched chain aliphatic, cyclic aliphatic, and aromatic hydrocarbons. These products are separated by means of fractional distillation to produce the liquid fuel products. Plastic pyrolysis takes place at 300°C–9000°C. The plastic is first evenly heated to narrow temperature range without excessive temperature variations, followed by purging oxygen from the plastic pyrolysis chamber. The third step involves managing the carbonaceous char by-product before it acts as a thermal insulator and lower heat transfer to the plastic. The final stage involves condensation and fractionation vapours to produce a distillate of good quality and consistency[823].

The Pyrolysis process can occur under varying operating conditions which can be used as the basis of classification[845]. They can be distinguished on basis of residence time requirement for the pyrolyzed material in the reactor, feedstock particle size, the pyrolysis process temperature, and process heat rate among others. The four mechanisms are involved in thermal degradation of plastics. These mechanisms are end-chain scission or unzipping, mechanism, the random-chain scission/fragmentation mechanism, chain stripping/elimination of side chain mechanism and cross-linking mechanism. The mode of decomposition is a function of the type of polymer i.e., the molecular structure, for example cross-linking is common in thermosetting plastics when heated to high temperature that causes two adjacent “stripped” polymer chains to form a bond resulting in a chain network like in char formation[100, 823].

11.6.1.Catalytic Pyrolysis

In catalytic pyrolysis a suitable catalyst is used to facilitate the cracking reaction by lowering the reaction temperature and process time[100]. Catalytic pyrolysis reduces the product range in terms of carbon atoms number and often it peaks at lighter hydrocarbons characteristic the process temperature. Catalytic pyrolysis is cheaper and hence economically attractive[849].Optimization strategy in catalytic pyrolysis is to minimize use of the catalyst through reuse and the use of low quantities of catalysts. Benefits of catalytic pyrolysis include cost-effectiveness, less pollution from plastic wastes and less solid residues[100].

The process of catalytic cracking pyrolysis involves heating the plastic material plastic in inert environment in the presence of catalysts. The temperature range for catalytic cracking is between 350⁰C and 550⁰C. This process can be applied for the recycling of either pure or mixed plastics. It yields higher quality fuel oils as compared to thermal pyrolysis. The catalyst promotes decomposition reactions at low temperatures with low energy consumption, reduced costs, faster cracking reactions, increase process selectivity and increased yield of products with high added value[828]. In this process, a cracking vessel is used for storage of melted waste plastic in which the primary heating component for heating the waste plastic is done from a surface at the base of the cracking vessel with a second level heating being done at the upper surface of the cracking vessel. A cooling vessel for cooling cracked gas vaporized in the cracking vessel, which results in a cracked oil byproduct[850].

11.6.2.Mechanism of Catalytic Degradation

11.6.2.1. Depropagation

This is achieved by reduction in the molecular weight of the main polymer chains through successive attacks by acidic sites or carbonium ions and chain cleavage, yielding approximately C₃₀–C₈₀). Further, cleavage of oligomer fraction like through direct β -emission of chain-end carbonium ions produces gas and a liquid fraction (approximately C₁₀–C₂₅).

11.6.2.2. Isomerization

In isomerization mechanism, the carbonium ion intermediates are rearrangement by hydrogen- or carbon-atom shifts, which then leads to a double-bond isomerization of an olefin. Some other isomerization reactions include the methyl-group shift and isomerization of saturated hydrocarbons.

11.6.2.3. Aromatization

The intermediates of carbonium ion can undergo cyclization reactions, for hydride ion abstraction may first takes place on an olefin at a position removing several carbons from the double bond which results in the formation of an olefinic carbonium ion. Then carbonium ion may undergo intramolecular attack on the double bond.

11.6.3.Process/Steps

The steps involved in catalytic cracking are initiation, propagation, and termination.

11.6.3.1. Initiation.

This stage involves random breakage of the C–C bond on the main chain occurs upon heating to produce hydrocarbon radicals.

11.6.3.2. Propagation.

In the propagation stage, the hydrocarbon radical is decomposed into lower hydrocarbons such as propylene, followed by β -scission and abstraction of H-radicals from the other hydrocarbons resulting in a new hydrocarbon radical

11.6.3.3. Termination

This stage involves the disproportionation or recombination of two radicals: This involves the catalytic degradation with Iron activated charcoal in presence of hydrogen. The hydrogenation olefin i.e., hydrocarbon ion and the abstraction of the H-radical in the HC (hydrocarbon) or HC radical would produce radical and improve or enhance degradation rate. For reactions that occur below 400°C as well as fast reactions taking less than 1 hr, the existence of hydrocarbon radicals in the reactor is high causing readily recombination of these radicals as they don't move fast. As for iron (Fe) activated carbon in presence of hydrogen, the radicals are hydrogenated which suppresses recombination. Therefore, the decomposition of the solid products is promoted. The same applies for the low polymers whose molecular diameter is larger than the catalysts' pore size [823].

11.6.4.Characteristic and Application of Pyrolysis Oil

Pyrolysis oil has similar characteristics with light fuel or gas oil and has proven to be a good furnace and engine oil but requires property modifications [851]. Modification can be achieved by use of alcohols to modify corrosiveness, acidity, ignition temperature, calorific value and volatility, as well as energy density. Blending with alcohols also reduces the negative environmental impact caused by pyrolysis oils. For use in as engine fuel, blending with up to 20% alcohol can be done with no engine modifications. The higher latent heat of vaporization of methanol and ethanol compared to diesel initiates longer ignition delay period of combustion with pyrolysis oil.

Pyrolysis oil from tyres and plastics has been tested and proven to be a feasible diesel engine fuel and have comparable properties to conventional diesel oil. The oil is a complex mixture of C5-C20 organic compounds. However, oil from tyres pyrolysis contains a higher proportion of aromatics and as high as 1.4% sulphur content. Unsorted plastics may also lead to higher chlorine content. There is however more need for more research on the costs of substituting fossil fuel with pyrolysis oil[841].

Oil from plastic wastes has got higher sulphur content compared to the conventional fuel making it unattractive as automobile fuel and increases sulphur dioxide emissions which is major contributor to acid rain. In a study on oil from pyrolysis of high-density polyethylene, the waste plastic pyrolysis oil (WPPO) was found to have sulphur content of 0.246% which is significantly

higher than conventional gasoline, kerosene, and commercial grade diesel. Conventional diesel has about 0.15% and 0.014% for gasoline. In other studies sulphur content of thermal pyrolysis oil was found to be 4.8% and catalytic 4.36% pyrolysis oil processed from mixed waste plastics [814]. Figure 11-4 shows the sulphur content of waste plastic pyrolysis oil (WPPO), heavy fuel oil, furnace oil, diesel, kerosene, light fuel oil and gasoline.

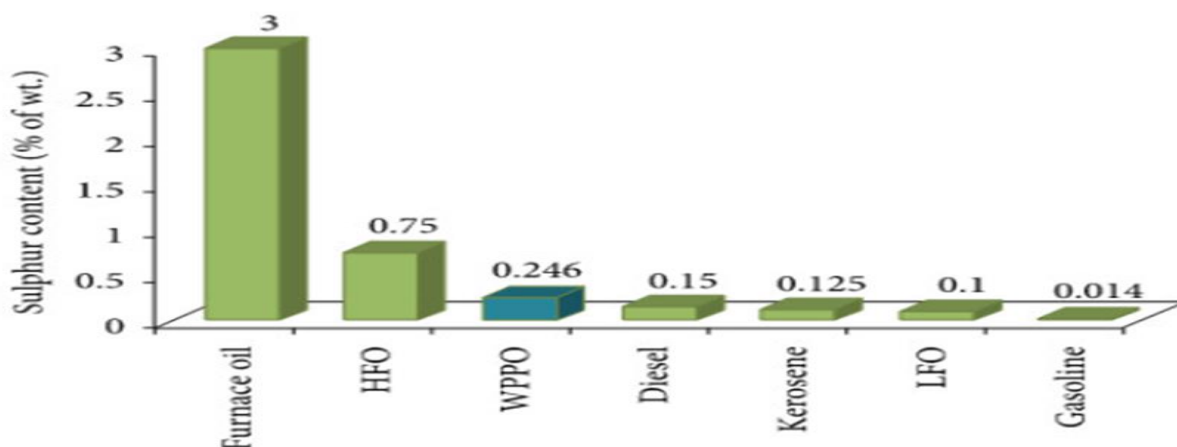


Figure 11-4: Sulphur content for various oils [814]

From Figure 11-4, it is noted that waste plastic pyrolysis oil has got higher sulphur content compared with conventional diesel, kerosene, light fuel oil and gasoline. However, its sulphur content is lower compared to that of heavy fuel oil and furnace oil.

The flashpoint for pyrolysis oil from plastic waste is < 40 degrees, but exact value varies based on type of plastic used as feed stock, for example a single feed plastic like polyethylene yields oils with flash point as low as 10 degrees compared to the flash point of conventional diesel being about 50 degrees. The low flash point is an indication of high volatility which is a safety concern in transportation[814].

Oil from tire pyrolysis yields better engine performance while the heating value of the plastic pyrolysis oil is higher than that of tire pyrolysis oil. Economically pyrolysis oil can replace conventional diesel oil in terms of engine performance and energy output as long as the price of pyrolysis oil is less than 85% the price of conventional diesel[841]. According[813] to crude oil prices above \$65 per barrel is necessary to justify commercial investment in waste plastic to fuel without a premium, but with a green premium, recycling waste plastic to fuel is still viable at prices below \$ 65 per barrel. A diesel engine was noted to give better performance

with up to 30% being pyrolysis oil and it may perform well with a maximum up of up to 50% waste plastic oil blended to conventional diesel. In another study by [823, 852] it was observed that an engine has stable performance with brake thermal efficiency being comparable to that of conventional diesel and the value of brake thermal efficiency is higher with pyrolysis oil up about 80% engine load. However, the engine emissions were notably higher with pyrolysis oil compared to the conventional diesel [841].

In a study on a petrol engine fuelled by waste pyrolysis oil, the engine had a higher brake thermal efficiency up to 50% of the petrol engine rated load. The higher calorific value and more oxygen content of the waste pyrolysis oil leads to higher heat release rates [824, 853, 854]. In another study by [824, 855] it was observed that high viscosity with blends, is the reason for poor atomization which leads to longer ignition delay and a longer combustion duration compared to conventional diesel when tested at full load. In other studies, by [824, 856-858] it was noted that the use of waste plastic pyrolysis oil increases ignition delay by about 2.50 CA. The study also noted increase in emissions with NO_x increasing by 25%, CO increased by 5% and Unburned hydrocarbon increased by about 15%, and smoke although smoke reduced by 40% to 50%. In yet another study by [859], waste plastic pyrolysis oil yielded brake thermal efficiency (BTE) 27.75% compared to 28% for diesel, brake specific fuel consumption (BSFC) of 0.292 kg/kWh compared with 0.276 kg/kWh for diesel, , unburned hydrocarbon emission (uHC) of 91 ppm compared with 57 ppm for diesel, and NO_x emission of 904 ppm compared with 855 ppm for conventional diesel.

An important parameter in combustion performance is injection timing for all compression ignition engines. In the study by [6], injection timing was varied for an engine. The study showed that by changing injection timing from 230 bTDC (Before top dead centre) to 140 bTDC (before top dead centre), the emissions for NO_x, CO and unburnt CO reduced. In the study by [860] it was experimentally established that the brake thermal efficiency of blends is lower than that of conventional diesel but at 25% blending, there was similar performance between the blend and pure diesel as a fuel for the engine [853]. Therefore, the plastic pyrolysis oil could improve engine performance by through modification like injection timing. Economically, pyrolysis oil can replace diesel in terms of engine performance and energy output on condition that the cost or price at the point of usage is not more than 85% of conventional diesel oil [861] if crude oil prices is more than US\$ 65 per barrel [813].

11.6.5.Oil Yield of Different Plastics

There are three major products of pyrolysis of plastic waste namely liquid oil, gas and solid residue or char. Liquid oil results from condensation of vapours released from the reactor whereas gas is obtained from the non-condensable vapours and solid residue remains in the reactor [844, 862, 863]. In studies by [864-866] the liquid oil, gas and solid residue were analysed for their composition, yield percentages and potential applications. Liquid oil is the dominant of the products, followed by gas and finally the solid residue. However, the process conditions such as temperature, use of catalysts, feedstock type and retention time, could be altered to favour production of either liquid or gas. Additionally, [865] showed calorific values for the liquid oil produced from pyrolysis of HDPE, PP and LDPE plastic waste were close to those of commercial diesel and gasoline. For PS, PVC and PET, low calorific values were attributed to an aromatic ring within PS chemical structure, chlorine in PVC and benzoic acid in PET. The kinematic viscosity, density and flash point of the pyrolysis oil showed values near those of commercial diesel and gasoline[844]. According to [864] pyrolysis oil can be used as a good transport fuel when blended with diesel in ratios of 10%, 20%, 30% and 40% produced various engine performance characteristics. Table 11-2 compares liquid oil properties with those of commercial grade diesel and gasoline.

Table 11-2: Physical properties of pyrolysis oil from different plastic waste[867]

Property	PET	HDPE	PVC	LDPE	PP	PS	Gasoline	Diesel
Calorific value (MJ/kg)	28.2	40.5	21.1	39.5	40.8	43.0	42.5	43.0
Density (g/cm ³)@15°C)	0.9	0.89	0.84	0.78	0.86	0.85	0.78	0.807
Viscosity (mm ² /s)	-	5.08	6.36	5.56	4.09	1.4	1.17	1.9-4.1
Flashpoint (°C)	-	48	40	41	30	26.1	42	52

The properties are also diagrammatically presented in Figure 11-5.

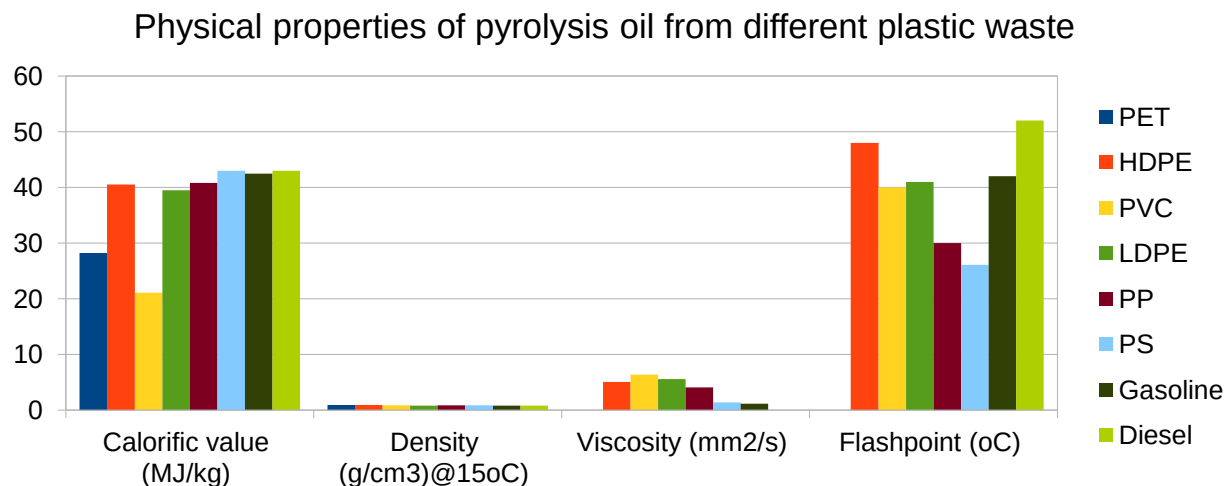


Figure 11-5: Physical properties of pyrolysis oil from different waste plastics

From Table 11-2 and Figure 11-5, it is noted that different plastics produce different outputs in terms of composition of the main products, i.e., oil, gas, and char. In terms of calorific value, polystyrene (P) produces oil with same calorific value as conventional diesel, but it has significantly lower flash point hence more flammable, it is more viscous and has higher density than diesel. Oil from PVC has the lowest calorific value. The pyrolysis oil is more viscous and has lower flash point than conventional diesel. Compared to petrol, pyrolysis oil has got higher density, but its flashpoint may be less or higher than pyrolysis oil depending on the oil source or plastic used[360].

The quality of pyrolysis oil is a function of both the type of plastic used and the process used. Table 11-3 is a summary of the process, type of plastic and the product quality realized.

Table 11-3: Summary of plastic pyrolysis studies[830]

Summary of studies on plastic pyrolysis.

Type of plastic	Reactor	Process parameters				Yield			Others
		Temperature (°C)	Pressure	Heating rate (°C/min)	Duration (min)	Oil (wt%)	Gas (wt%)	Solid (wt%)	
PET	Fixed bed	500	–	10	–	23.1	76.9	0	
PET	–	500	1 atm	6	–	38.89	52.13	8.98	
HDPE	Horizontal steel	350	–	20	30	80.88	17.24	1.88	
HDPE	Semi-batch	400	1 atm	7	–	82	16	2	Stirring rate 200 RPM, FCC catalyst 10 wt%
HDPE	Batch	450	–	–	60	74.5	5.8	19.7	
HDPE	Semi-batch	450	1 atm	25	–	91.2	4.1	4.7	Stirring rate 50 RPM, FCC catalyst 20 wt% Silica alumina catalyst
HDPE	Fluidized bed	500	–	–	60	85	10	5	
HDPE	Batch	550	–	5	–	84.7	16.3	0	
HDPE	Fluidized bed	650	–	–	20–25	68.5	31.5	0	
PVC	Fixed bed	500	–	10	–	12.3	87.7	0	
PVC	Vacuum batch	520	2 kPa	10	–	12.79	0.34	28.13	Also yield HCl = 58.2 wt%
LDPE	Pressurized batch	425	0.8–4.3 MPa	10	60	89.5	10	0.5	
LDPE	Batch	430	–	3	–	75.6	8.2	7.5	Also yield wax = 8.7 wt%
LDPE	–	500	1 atm	6	–	80.41	19.43	0.16	
LDPE	Fixed bed	500	–	10	20	95	5	0	
LDPE	Batch	550	–	5	–	93.1	14.6	0	
LDPE	Fluidized bed	600	1 atm	–	–	51.0	24.2	0	Also yield wax = 24.8 wt%
PP	Horizontal steel	300	–	20	30	69.82	28.84	1.34	
PP	Batch	380	1 atm	3	–	80.1	6.6	13.3	
PP	Semi-batch	400	1 atm	7	–	85	13	2	Stirring rate 200 RPM, used FCC catalyst 10 wt% Stirring rate 50 RPM, used FCC catalyst 10 wt%
PP	Semi-batch	450	1 atm	25	–	92.3	4.1	3.6	
PP	–	500	1 atm	6	–	82.12	17.76	0.12	
PP	Batch	740	–	–	–	48.8	49.6	1.6	
PS	Semi-batch	400	1 atm	7	–	90	6	4	Stirring rate 200 RPM, used FCC catalyst, cat/poly = 10 w/w
PS	Pressurized batch	425	0.31–1.6 MPa	10	60	97	2.50	0.5	
PS	Batch	500	–	–	150	96.73	3.27	0	Used Zn catalyst, cat/poly = 5 w/w 64.9 wt% of liquid comprised of styrene
PS	Batch	581	–	–	–	89.5	9.9	0.6	

* All experiments used nitrogen gas as fluidizing medium.

Table 11-3 above shows the various plastics, the oil yield potential, and optimum conditions for pyrolysis and solid waste generation. The pyrolysis temperature used is between 350 and 740°C. The highest oil yield is 97% oil yield from polystyrene processed in a batch reactor at 425°C.

Fuel can be produced from plastics through gasification, thermal pyrolysis, and catalytic pyrolysis. Catalytic pyrolysis of homogenous waste plastics generates better oil in terms of both quantity and quality. The main product of gasification is syngas at higher temperature than those realized in the pyrolysis process. Syngas can be used as a feedstock for the Fischer-Tropsch (FT) process for production of diesel and other chemical products. The formation of tar in gasification can be reduced by application of Olivine as bed material [62, 386, 859].

11.6.6.Char and Gaseous Products

The pyrolysis gas produced mainly consists of methane, hydrogen, ethane, propene, propane, and butane. The gas produced is a function of the feedstock material used and the process parameters. Carbon dioxide (CO₂) and carbon monoxide. (CO) are produced when the feedstock contains PET material while hydrogen chloride gas is produced as an addition gas if PVC is part of the feedstock [814, 823]. The pyrolysis gas has potential internal use as source of energy for the pyrolysis plant process. Additionally, production of polyolefin the pyrolysis gas is feasible after extracting ethene and propane gas components[867]. Research by Reference [6] provided a summary of pyrolysis studies using various feedstock material, process parameters and product yield.

Solid residue or char produced during pyrolysis majorly consisted of volatile matter and carbon with low levels of moisture and ash. Its calorific value was estimated to be 18.84 MJ/kg, thus suitable for use as fuel, e.g., in combustion with coal. Upgraded chars are used in heavy metal adsorption from industrial wastewater and toxic gases. Other uses include energy source for boilers and feedstock for activated carbon[867].

11.6.7.Results and Discussion

Plastics are popular and have found wide range of applications because of the lightweight, they do not rust, don't rot, are cheap, are reusable and have significant socio-economic positive impact. However, plastics are non-biodegradable and huge quantities of plastic wastes have become a nuisance to the environment. Sustainable use of plastic wastes should encourage reuse, and recycling[2, 3].

Huge quantities of plastic wastes can be used as feedstock to produce fossil fuel substitutes. Plastic pyrolysis plants have been set up in several countries globally to convert waste plastic to hydrocarbon fuel which may be a cheaper partial substitute of the petroleum oil. Production of pyrolysis oil from plastic wastes is ecologically and economically superior to many other options since it addresses the environmental pollution and partially addresses the challenge of fossil fuel reserves depletion by reducing demand primary oil by acting as a substitute feedstock in production of lubricants and other oil products[12, 793]. The overall effect waste plastic pyrolysis is reduction in hazardous plastic waste as well as reduction import bill for oil importing countries.

The challenges facing plastic pyrolysis as a process for oil production is existence of limited standards for regulation of the process and products of recycled plastics and develop more efficient and cheaper pyrolysis technologies. Economic viability of plastic pyrolysis is dependent on design and development of suitable reactors to suit the wide range of plastic wastes feedstock with varying process requirements and product output. and a reduction in the capital investment capital investment and cost of operation and maintenance[100, 275].

Plastic production has been growing steadily since the first production in 1950s to date. Due their short life cycle, there is high rate of waste generation hence the need to recycle. More as only about 15% of plastic wastes are recycled globally. Studies have shown that thermal pyrolysis yields more char compared to catalytic pyrolysis. On the other hand, catalytic pyrolysis yields more liquid fuel than thermal pyrolysis. The average gas production is slightly higher in thermal pyrolysis compared to catalytic pyrolysis. Overall, the difference in output is close enough in terms of product output and the process plant designer would rather analyze other factors like cost in process selection although catalytic pyrolysis is superior in terms of solid remnants that should be landfilled[57, 100, 360].

Not all stakeholders are positive about the rationale of converting plastics to fuel. Some environmentalists have argued that widespread adoption of plastics to fuel could slow down efforts to develop sustainable alternatives to fossil fuel use work against the effort to realise zero emissions by 2050[837]. Further analysis shows that pyrolysis as a recycling measure has a lower carbon footprint incineration even though it has significant energy potential[813].

11.6.8.Conclusions

Plastics consumption and production has been growing since first production in 1950s. About 4% of global oil and gas production, being used as a feedstock for plastics and 3 –4% used to

provide energy for their manufacture. The short lifecycle of many plastics and wide use in domestic and industrial applications has led to significant quantities of plastic wastes globally. Plastics demand is high globally and it continues to grow mainly because of their flexibility and affordability for wide range of industrial and commercial application. There are many strategies and options for plastic recycling classified as primary, secondary, tertiary, and quaternary recycling techniques. There are four main avenues available for plastic solid waste treatment, namely re-extrusion as a primary treatment, mechanical treatment as secondary measures, chemical treatment as a tertiary measure and energy recovery as a quaternary measure. Various operations involved in plastic recycling include separation, sorting, and cleaning of the wastes. Main challenges facing plastic recycling include high collection and transport costs, high electricity bills, and feed stock wide variation of quality and properties of different plastic types.

This study proved the significance of plastic waste recycling as a means of combating greenhouse gas emissions from energy sector as use of waste plastic as a source of alternative high value fossil fuel. The study showed that plastic pyrolysis is cleaner, efficient, technically, and commercially way of plastic waste disposal which besides solving environmental crisis from solid waste disposal will generate fuel revenue and savings by producing alternative fossil fuel which would reduce demand for primary fossil fuels and hence related environmental costs and resource depletion. The best and most sustainable solution to plastic pollution is recycling. There are various methods of plastic recycling like primary, secondary, tertiary, and quaternary recycling.

Plastic pyrolysis is an attractive option for plastic waste as many authorities and countries globally call for a ban of several of plastic categories from the market due to failure by the conventional methods of plastic waste control to address environmental pollution by plastic wastes. The process however still faces several limitations particularly with respect to collection, separation, sorting and cleaning operations and high cost of power and transportation.

Other than liquid pyrolysis oil, hydrocarbon rich gas is produced having heating value of 25–45 MJ/kg which makes it ideal for process energy recovery. Hence the pyrolysis gas can be fed back to the process for extraction the energy for the process heating purpose which reduces the reliance on external heating sources. A leading challenge in plastic recycling is the recycling of mixed plastics waste. The main advantage is the ability to Rec considerable proportion waste stream through postconsumer collection of plastics to include wider variety

of materials and pack types. More opportunities for recycling are being created by technological advances in technologies and systems applied for collection, sorting, and processing of used plastics aided by the combined effort of the public, environmental authorities, industry, and governments to ensure that majority of plastic waste are recycled.

11.6.9.Recommendations

This study recommends furthermore, investigation into the best waste to energy conversion process for cost effective waste plastic recycling and performance of various biodiesel and waste plastic pyrolysis oil to increase the green value of plastic pyrolysis oil production. The study additionally recommends plastic waste liquefaction as another recycling pathway for enhanced application of plastic wastes in production of products like naphtha by converting polymers to liquid chemical products. Research into the economic and technical feasibility of bioplastics is recommended as a strategy of improving plastic recycling. A well-established plastic waste collection system is necessary for proper success plastic waste recycling. Through continues awareness, the public will support recycling effort as contributor's ad users of the plastic wastes and pyrolysis oil. The government should provide a conducive environment for plastic waste recycling through policy and legal measures as well as economic and financial.

11.7. Cogeneration for Diesel Power Plants

In most heat engines, more than 50% of the primary energy in fuel is wasted. Cogeneration makes use of waste heat that would have otherwise been wasted in a conventional powerplant then increases efficiency to as high as 80% to 95%, instead of about 40% that can be realized in conventional powerplants[868]. Diesel engines have the highest thermal efficiency compared to all heat engine prime movers of similar size and capacity. The engines can be classified as two stroke or four stroke engines. Other mode of classifying diesel engines includes the number of cylinders, i.e., single cylinder or multicylinder among others[275]. Compared to otto cycle or petrol engines, diesel cycle engines can operate with high compression ration which makes them have higher power density and slower engine specific volume which makes them versatile and compact as well as more efficient than otto cycle engines[869].

An ideal diesel cycle process follows four thermodynamic processes, i.e., constant pressure combustion, isentropic compression, expansion, and constant volume cooling. The diesel powerplants have many advantages which include small area requirements, high thermal

efficiency, and simple construction layout of the power plant[114]. On the other hand, the disadvantages of diesel power plant cannot be ignored which as well makes them attractive for many applications like emergency power supply, off grid power supply, standby units, and in some cases, diesel powerplants are used in base load grid power supply whenever cheaper and cleaner sources become limited. They however have limitations like high cost of fuel and electricity, high emissions of greenhouse gases, high operation and maintenance costs and low reliability of supply [114, 869].

Internal combustion engines release about 30-40% of the fuel energy content as waste heat in the exhaust gas and about 30 to 40% is released through the cooling system [870]. These waste heat can be recovered for thermal applications and in some cases power generation through a Rankine cycle [871]. The recovery of waste engine heat for valuable application reduces the fuel consumption and related negative environmental impact which includes NO_x and SO₂ emissions while producing the same power output [21, 101]. Therefore, engine waste heat recovery is a proven strategy for mitigation against excessive use of fossil fuels hence reduced environmental pollution and can process heating costs and fuel energy costs. Diesel engine exhaust can supply extra mechanical power using the Rankine cycle in which the working fluid is water with about 38% extra power potential through waste heat recovery with optimum pressure of about 30 bars [872].

Internal combustion engines consume more than 60% of fossil fuels for their application as prime movers in agriculture machines, fishery, transportation, construction, power generation [873]. While about 60% of air pollution comes from internal combustion engine exhausts [873, 874]. An engine's main output is mechanical power which can be used to turn a generator for power generation and waste heat in the exhaust and cooling system which can be recovered for thermal applications [496]. The mechanical output can also be used for rotation of equipment such as compressors, pumps, and other machinery.

11.7.1.Cogeneration Potential for Kipevu III Diesel Engine Power Plant

11.7.1.1. Introduction

The content of this section is published by in papers co-authored by the supervisor, Prof. Oludolapo. The study covered Kipevu III power plant located in Mombasa, Kenya. This power station uses a conventional method of electric power generation which is achieved by rotating a generator directly coupled to a seven 17.1 MW capacity V-engines. engine which releases exhaust gases at elevated temperature to the atmosphere. This is wasteful as

recoverable heat energy is wasted to the environment through exhaust heat and the engine cooling and lubrication system. In this, a study performance analysis was done to determine the performance of the 119.7 MW Kipevu III power plant and feasibility of developing a cogeneration plant using a Rankine cycle steam turbine with exhaust gas boiler for waste heat to steam conversion. It was established that about 10 MW extra electric power can be generated by developing a Rankine cycle cogeneration plant from the combined 119.7 MW Kipevu III diesel engine power plant hence 8.4% extra electric power. This will lead to dual benefit more power output and hence revenue, reduced impact on the environment by avoiding use of extra oil to generate up to 8 MW power and reduced cost of power because of lower specific fuel generation and profits on fuel energy consumed. Therefore, cogeneration is a more efficient use of fuel in diesel engine power plants with financial, energy and environmental benefits.

The high efficiency of compression-ignition or diesel engines has endeared themselves as a leading power source in transport especially heavy-duty vehicles and in diesel powerplants. The engines are also finding themselves in light-duty cars which were dominated by petrol or gasoline engines. The main challenge of diesel engines is the emissions mainly in the form of carbon dioxide, NO_x due to oxidation of nitrogen in the air at high combustion temperatures, particulate matter (PM) and Sulphur dioxide from oxidation of Sulphur component of the fuel [391, 781, 875]. Diesel powerplants constitute diesel engines and auxiliary systems of the powerplants [5]. Diesel powerplants convert fossil fuels to electricity using diesel engines as generator prime movers[876]. The diesel power plants are widely used in off grid electricity generation, emergency power applications and grid electricity supply mainly as peak load and emergency power plants especially in developing countries [877]. Other than fossil fuel combustion in coal and diesel power plants, there are various generation technologies like cogeneration that can be used to generate electricity cost effectively while reducing carbon emissions [499]. Diesel power plants are mainly used as standby generating units alongside grid power supply or grid connected units for supply of peak power [330, 878]. The construction of diesel power plants consists of the diesel engine prime mover, the generator set and supporting auxiliaries and systems[878]. Because of size limitation of engines and the need to inbuilt flexibility in the power generation capacity and output, a diesel power plant consists of multiple generating units. For the case of Kipevu III power station, 7 engines of 17.1 MW installed capacity are used hence the power plant capacity is 119.7 MW [879].

11.7.1.2. Materials and Methods

The contract for construction of Kipevu III diesel engine power plant was signed on November 27, 2009, with the project contractor being Wartsilla. Kipevu III diesel engine powerplant is located at Kipevu in Mombasa and was commissioned in the 2011., with the commissioned plant being handed over on March 6, 2011, to Kenya Electricity Generating Company (KenGen)[879]. The powerplant is the largest grid connected diesel engine power plant in East and Central Africa, having installed capacity of 119.7 MW connected to the Kenyan national grid through a 132KV switch yard extension [880]. The powerplant is equipped with seven Wärtsilä 18V46 turbocharged diesel engines[879].

The power station on average has effective of 117 MW with auxiliary equipment consuming part of the 119.7 MW installed generation capacity[881]. The plant employs the latest technology in plant operations monitoring and supervision, plant safety, sound attenuation and exhaust gas dispersion control and efficient treatment to ensure environmental protection [880, 881].

The design of a diesel engine powerplant involves optimal sizing of the various units that constitute a powerplant. This includes a careful consideration of daily and seasonal load fluctuations, electricity demand growth, incorporation of practical constraints to ensure flexibility and reliability of the plant and economic operation and maintenance. To avoid oversizing of the power plants, the individual units should not be sized based on peak and/or average load values alone. Consideration should be made for some safety margins and future demand and capacity based on projections made. A practical approach in the design of a power plant is use multiple units, like a set of two, three or four engines with varying sizes. For maximum fuel efficiency, engines should be loaded in a way that maximizes cycle efficiency and use a dispatch strategy that optimizes the powerplant performance[877].

Kipevu III power station is a diesel engine powerplant located at Kipevu in Mombasa County that was commissioned in the year 2011[879]. The construction of the powerplant officially started with the signing of a construction on November 27, 2009, between the Kenya Electricity Generating Company Plc. (KenGen) as the owner or employer and Wartsila Finland as the contractor. The powerplant was constructed, commissioned, and handed over to KenGen for operation and maintenance on March 6, 2011. The powerplant so far the largest diesel engine power plant in East and Central Africa with 119.7 MW connected to the national grid through a new 132KV switch yard extension [880]. The power plant is owned

by Kenya Electricity Generating Company Limited (KenGen) who have a 20-year power purchase agreement with the grid electricity utility company, the Kenya Power Plc[879]. The power plant has a total of 7 Wärtsilä 18V46 turbocharged diesel engines individually exhausting the products of combustion as exhaust gases to the atmosphere via a turbocharger [879]. The effective capacity of the power plant is 117 MW with the auxiliary units consuming about 2.7 MW electric power [881]. The power plant (Kipevu III) employs the latest technology in plant monitoring and supervision, safety, sound, emission monitoring and provisions emission treatment to ensure environmental protection and compliance [880, 881].

A cogeneration power plant design requires the selection of most economic combination of equipment and technology from the many available alternatives. This technology is chosen based on the energy forms required by the user which may include Heat Recovery Steam Generator (HRSG). The important factors that play a key role in determining the plant configuration is the available fuel and the ratio of heat demand to power demand. The proposed cogeneration plant has one exhaust gas recovery boiler that gets exhaust gas supply through connection to the exhaust ducts of the 7 diesel engines. Steam generated is directed to the Rankine cycle steam turbine to which rotates a synchronous electric generator for grid connected electricity generation.

Kipevu III diesel powerplant has 7 similar diesel engines and generators. The engine specifications are summarized in Table 11-4.

Table 11-4: Kipevu III Engine Specifications [879]

Manufacturer	Wärtsilä
Type of engine (operating strokes & orientation)	18V46
Bore	460mm
Stroke	580mm
Number Of Pistons	18
Compression ratio	22:1
Power output	17.1 MW
No of generating units	7
Speed (RPM)	500 RPM
Cooling system	Water Cooled
Exhaust Gas Temperature	360 °C

Compression Pressure	190 bars
Specific Fuel Consumption	0.1818 <i>kg/kWh</i>
Swept Volume Capacity	96,390 cc
Mean Effective Pressure	24 bars
Mean Torque	318.946kNm

Table 11-4 summarizes the specifications of the engines and the power plant.

11.7.1.3. The Power Plant Performance Analysis

i. Availability and load factor for the powerplant

The performance of the powerplant in terms of load factor and availability is summarized in Table 11-5.

Table 11-5: Kipevu III power plant performance Indicators

FACTOR/YEAR	2017/2018	2016/2017	2015/2016	AVERAGE
1.Load factor	58.93	50.84	17.66	42.48
2.Availability	89.6	93.05	97.84	93.50

From Table 11-5, it is noted that between 2017/18 and 2015/2016 financial years, average availability was 93.5% while average load factor was 42.48% while. This implies that although the plant was available most of the time, its demand was low.

ii. Indicated Power

$$\text{Indicated Power (IP)} = \frac{\text{Imep} \times \text{Ac} \times \text{L} \times \text{N} \times \text{n}}{2 \times 60} = \approx 17\,350.236 \text{ kW}$$

Therefore, the indicated power which corresponds to fuel power is about 17.35 MW.

iii. Brake Power

Engine brake power is the actual power output of an engine and is measured by means of a dynamometer on the test bench.

$$\text{Break Power} = \frac{2\pi NT}{60} \text{ Where N is engine speed, T engine torque} = 16699.973 \text{ kW}$$

iv. Efficiency

Mechanical efficiency of an engine is the ratio of brake power to indicated power and it is a measure of energy conversion to useful power from the power developed in the cylinder.

$$\eta = \frac{\text{Brake Power}}{\text{Indicated Power}} \times 100\% = \frac{16,699.973}{17,350.236} = 96.25 \%$$

v. Mass flow rate of exhaust gases

Mass flowrate is the rate of flow of the flue gases in kg/sec. the total mass of flue gases for a closed system is the sum of combustion air and the fuel supplied to the furnace. Therefore.

$$m_{ex} = m_{fl} + m_{ar} = m_{ex} = 0.8433 + 5.3 = 6.144 \text{ kg/s}$$

vi. Heat loss by the exhaust gases (One engine unit)

This refers to technically recoverable waste heat or exhaust heat. Hence the exhaust contains Sulphur dioxide, the recommended minimum exhaust temperature is 170°C.

$$Q_{ex} = m_{ex} \times Cp \times \Delta T$$

Where ΔT is the temperature difference i.e. $(360 - 170) = 120$. This

represents technically recoverable heat energy in exhaust gases. $\Delta T =$

Thermal gradient, $Cp =$ Heat capacity of flue gases

$$Q_{ex} = m_{ex} \times Cp \times (T_{source} - T_{sink}), Q_{ex} = \frac{6.144 \text{ kg}}{\text{s}} \times \frac{1.008 \text{ KJ}}{\text{kgK}} \times (360 - 170) = 1176.69 \text{ Kw}$$

11.7.1.4. Design of Heat Recovery Steam Generator (HRSG)

A shell and tube heat exchanger are proposed for the heat recovery steam generator to extract heat from the engine exhaust. It receives exhaust gases from all the 7 engines. Heat Transfer area and tube numbers 1 shell and 2 tube passes 1" OD tubes (do) (14 BWG) on 1 1/4" square pitch (PT) Outer diameter of tube = 1, Tube length (Lt) = 16, Tube ID (di) = 0.834"

i. Heat Transfer Area

$$A = \frac{Q}{U_o (LMTD) F_T} = \frac{m_{ex} C_{pex} (T_{hi} - T_{ho})}{U_o (LMTD) F_T}$$

(LMTD) = Logarithmic mean temperature difference

Where LMTD is logarithmic mean temperature difference, $U_o =$ Overall heat transfer coefficient, T_{hi} and T_{ho} is temperature at inlet and outlet for hot fluid

$$A = \frac{1.394 \times 10^3 \times 7 \times 6.144 (360 - 220)}{60 (225.94) 0.98} = 631.78 \text{ m}^2$$

Figure 11-6 demonstrates the counterflow heat exchanger proposed for this design.

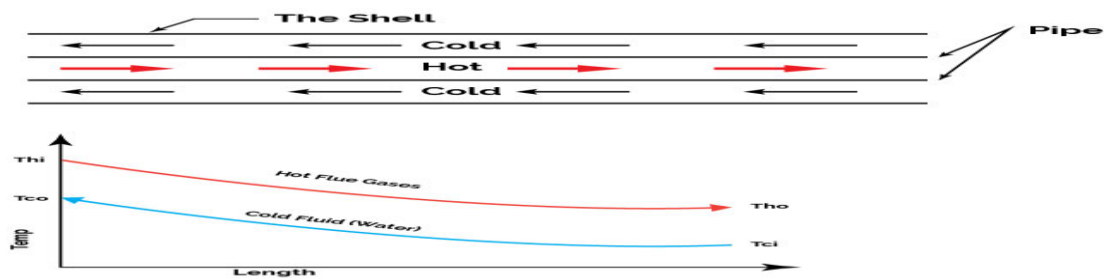


Figure 11-6: Temperature Distribution for Counter Flow Heat Exchanger (Authors Conception)

Figure 11-6 shows the temperature distribution for the two fluids i.e., flue gases as hot fluid and water/steam as the low temperature fluid in the heat exchanger. The flow gases flow in the tube side while the water flows through the shell side towards opposite directions.

ii. Shell diameter (Ds)

For a 1-shell and 2-pass heat exchanger, according to TEMA standards, for 1300 tubes, the minimum recommended shell diameter is 84 inches. $DS = 84 \text{ inches} = 84 \times 25.4 = 2133.6 \text{ mm}$

iii. Baffle Spacing and baffle cut.

According to the Tubular Exchanger Manufacturers Association (TEMA), the recommended baffle spacing is 0.2 to 1 time the inside shell diameter. $Baffle \text{ Spacing} = 0.4 \times 2133.6 \text{ mm} = 853.44 \text{ mm}$

Shell thickness: $t_s = \frac{PR_s}{\sigma_j - 0.6P} + \text{Corrosion Allowance}$

J is the efficiency of the joint, J for butt weld joint is 0.8., $t_s = 2.21 + 1.5 \text{ mm} = 3.71 \text{ mm}$

11.7.1.5. Design of a Super Heater (interface II)

The superheater is a heat exchanger that extracts heat from exhaust gases to heat wet steam with the objective of generating superheated steam.

- i.) Specific heat capacity of steam ($C_{p_s} = 2.01 \text{ kJ/kgK}$)
- ii.) Specific heat capacity of the flue gases ($C_{p_f} = 1.1394 \text{ kJ/kgK}$)
- iii.) Mass flow rate of steam = 18 kg/s
- iv.) Mass flow of flue gases = 43.008 kg/s
- v.) Diameter(outer) of the tubes = 1.5 inch (38.1mm)

- vi.) Length of the tubes = 4 meters
- vii.) The heating surface area, (LTSH) = 3055 m²
- viii.) Desired efficiency of the super heater = 0.9

The number of tubes for the heat exchanger.

$$n = \frac{A_o}{\pi \times D_o \times L}, n = \frac{3055}{\pi \times 0.0584 \times 6} = 2775 \text{ tubes}$$

Therefore, the exhaust gas heat recovery system will have 2775 tubes.

11.7.1.6. The Steam Turbine

Steam velocity exiting the nozzle= 15000 rpm; Tangential component of velocity out of nozzle is twice the blade speed; Tangential component of absolute velocity out of rotor is zero, High head of about 100m since it's an impulse turbine; Mass flow rate of steam, 18 kg/s (unit)

$$U = \omega R_m, \quad U = \frac{15000 \times 2\pi \times 0.71}{60} = 111.53 \frac{m}{s}; \quad W_{shaft} = -(2U^2) = 2 \times 111.53^2 = -24,876.34 \text{ Nm}$$

11.7.1.7. Steam Turbo- Generator Design Selection

The turbine selected for the cogeneration application in this design is summarized in Table 11-6.

Table 11-6: Steam Turbo- Generator Selection

Type	SST-200, Single-casing, geared
Application	Industrial use
Model	Multivalve Multistage (MVMS)
Turbine Design	Condensing turbine
Generator type	Synchronous
Power Output	Up to 10MW
Inlet Pressure	Up to 110 bars
Inlet Temperature	Up to 520°C
Exhaust Pressure (condensing)	Up to 0.25 bar

Exhaust area	0.17 – 0.34 m ²

From Table 11-6, it is noted that for optimum design and operation, the turbine will be multistage condensing type with condenser pressure of 0.25 bars, design inlet steam temperature is 520°C, inlet steam pressure is 110 bars, power rating is 10 MW, generator type is synchronous for constant frequency generation,

11.7.1.8. Results and Discussion

The proposed extension plant recovers heat from the exhaust of the diesel engines to generate superheated steam to run a steam turbine which rotates an electric generator to produce extra electricity for supply to the grid. This requires the water treatment system for treatment of boiler water for steam generation, the heat recovery steam generator (HRSG) which recovers heat from flue gases for generation of wet saturated steam from water, a superheater for generation of dry steam by heating saturated steam from the HRSG, a steam turbine for conversion of energy in steam to mechanical power, a generator which is coupled to the steam turbine for power generation, and a condenser for condensing turbine exhaust to water which is recovered and stored in a water tank or feed water tank. A feed water pump is used to pump the condensate and any make up water to the HRSG for another cycle of steam generation. Figure 3 below shows the main elements of the proposed Rankine cycle plant for Kipevu III.

It is noted that the main elements of the proposed Rankine cycle plant for extra electricity generation include the already existing 7 engines which supply exhaust gas, the heat Recovery steam Generator (HRSG), superheater, the condenser, feed water pump, impulse steam turbine interconnected with various pipelines and electric generator which is coupled to the steam turbine for conversion of mechanical power to electricity.

Cogeneration or CHP (Combined Heat and Power) solutions can generate heat and power simultaneously effectively increasing the overall efficiency of the system up to 90% and even more based on the lower calorific value. This is high compared to the average of 30–35% for conventional fossil fuel fired powerplants and 55% for the combined cycle power plants like the combined cycle gas turbine powerplants. Higher energy efficiency can result in lower energy expenditures and lower greenhouse gas emissions per unit generation. This potentially reduces the overall energy expenditures and unit cost of power generation which can be passed to consumers. Cogeneration can be applied on various prime movers other than diesel

engines. They include gas turbines, Stirling engines, fuel cells, and geothermal powerplant systems.

Cogeneration's systems can be designed or sized for various plants based on the thermal and electrical needs and thermodynamic conditions. Cogeneration is also a leading source of distributed generation which can enhance power system reliability and help reduce transmission losses because there is no need to transport power over long distances. Cogeneration also reduces electricity load or demand for heating purposes hence reduced need for polluting generation. Through cogeneration, less primary energy resources are consumed to deliver the same amount of useful energy and hence less pollution from reduced energy consumption to do same work. Therefore, cogeneration has an important contribution to climate change mitigation while offering economic and social benefits to society.

11.7.1.9. Conclusion

Engines account for about 60% of fossil fuels for their application as prime movers in and 60% of air pollution. Kipevu III power plant has installed capacity of 119.7 MW consisting of 7 engines with effective electricity capacity of 17.1 MW from the installed generation capacity of 119.7 MW. The engines exhaust recoverable waste heat of about 1,176.69 KW per engine and a total of about 8,236.83 KW for the 7 engines. Therefore about 8 MW extra electric power can be realized by developing a Rankine cycle cogeneration plant from the combined 119.7 MW Kipevu III diesel engine power plant hence 6.7 % extra electric power. This will lead to triple benefit more power output and hence revenue, reduced impact on the environment by avoiding use of extra oil to generate 8 MW power and reduced cost of power because of lower specific fuel generation. More power can be achieved by optimization of the design and adoption of more efficient cycles like the organic Rankine cycle. Diesel power plants can reduce power cost by exploring the best power producing practices such as cogeneration which increases the power output from same fuel leading to lower specific fuel cost and lower cost of produced power. The payback period for direct investment is as low as 1 year although indirect project cost may increase the period. The analysis shows that the development of a cogeneration plant on the existing power plant is both technically and economically feasible.

11.7.1.10. Recommendations

Based on these results, the authors recommend that diesel engine power plants should include cogeneration to increase the capacity, reduce electricity cost and mitigate greenhouse gas

emissions through avoided generation of electricity produced from waste heat. These should be enforced through financial and investment incentives as well as legal instruments.

11.8. Diesel to Natural Gas Power Plants

The content of this section is published by the author in publications [30, 113, 279, 284]. This study proposed conversion of Kipevu III diesel engine power plant to a natural gas-powered plant with the objective of reducing emissions and cost of power by avoiding and reducing generation from heavy fuel oil. The study showed that the use of natural gas simultaneously reduces the cost of generation per kWh and emissions, particularly SO_x. The conversion process involves modification of the fuel injection system to cope with new fuel injection and ignition requirements, new control for fuel injection and reduced air to fuel ratio and lowering of the engines' compression ratios through increase of the engine cylinder clearance volume. These fuel savings will influence renegotiation of the power purchase agreement resulting into lower tariffs, higher load factor and power plant utilization which translates to more revenue and reduced unit cost of power with lower environmental impact as well as better return on investment from the largest grid connected diesel power plant in East and Central Africa. This study showed that dual fuel diesel power plants running on both natural gas and diesel exhibit better performance indicators in terms of engine specific fuel consumption, engine brake thermal efficiency, diesel engine indicated thermal efficiency, the power plant electricity generating unit cost of power, the total engine emissions and hence leading to less environmental impact. Therefore, the engine fuel conversion will reduce the cost of electricity generation and amount of pollutants associated with diesel in power generation.

11.8.1.Introduction

Diesel engines have many engineering applications transportation, marine applications, and stationary power generation among other due to their relatively higher reliability and fuel efficiency compared to spark ignition engines and other prime movers. However, high emission has become a serious concern [882-884]. Many countries globally have enacted severe emission regulations due to concerns over Climate change. This has generated demand for more sustainable fuels for internal combustion engines like natural gas which can be produced from renewable sources.[885]. The changing climatic conditions, strict environmental regulations, high cost of diesel power generation and general sustainability concerns have created need for cleaner and cheaper fuels for diesel power plants [886].

11.8.1.1. Conversion of Diesel Engines to Gas Engines

It is possible to convert a diesel engine to a full natural gas engine but for this to work, several modifications should be done to the conventional engine [477]. These modifications include the following:

- i.) Removal of the engine fuel injector pump and fuel injection nozzles.
- ii.) Reduction in the engine design compression ratio to prevent fuel pre-

ignition by increasing the stroke volume. Although a higher the compression ratio leads to more power by the engine, the degree of compression is limited by the octane number of the fuel used by the engine. High compression ratio when applied to fuels with low octane number causes knocking[186, 495, 887]. Compression ratio can be reduced by exchanging the piston for one that effects a lower compression ratio than the compression ratio for conventional diesel engine or machining off some material from the piston top and modify the piston groove or machine off some material from the combustion chamber side on the cylinder head, The piston is modified by use of thicker cylinder gasket [114, 477].

iii.) Modification also involves the introduction of an ignition system with distributor, ignition. coil, and spark plugs for ignition for the gas fuel. The ignition system selected for use is mainly a function of the number of cylinders of the engine. For a single cylinder engine, a transistor type system may be required and often a magnet is installed on the flywheel. But the multi-cylinder engines require installation of an ignition distributor [30, 477, 888].

Natural gas requires the ignition system since it does not self-ignite like diesel hence the need for the ignition system in the place of the fuel ignition system for the original diesel engine. A battery ignition system can be used, and it comes as contact (breaker) point type or the electric ignition system The main elements of the breaker point type system are the breaker point gap, dwell angle, and rubbing block gap, which are essential for performance of ignition system. For the transistorized ignition system, a signal generator is needed for the distributor in place of the cam and breaker point which are used in the breaker point type of battery ignition making them more appropriate for the converted diesel engine.[30, 113, 279, 284, 887].

Another important device is the spark plug whose size is selected based on engine power and cylinder size. To set up the spark plug there is need to drill the cylinder head to set a nozzle hole with a diameter of spark plug[887, 889]

iv.) Installation of electricity supply system (alternator)

Modification also requires the introduction of an ignition system for conversion to a spark ignition system with an alternator and electricity storages devices mainly in form of batteries with a charge regulator. Some diesel engines already have alternators and batteries for the stator which can serve the purpose, hence this may not be a mandatory modification to the conventional engine.

v.) Installation of a fuel mixing device/ system

This is needed to mix the air and fuel for supply to the combustion chamber. This may consist of a venturi mixer, a simple mixing tank or pneumatic control valve [477]. For a diesel engine to run on natural gas, the natural gas intake should be modified for proper mixing of air-gas mixture. Appropriate pipes for air and gas are needed to provide correct air-gas ratio and adequate quantity of air and gas. The design is guided by the engine rating, size, air fuel ratio and cylinder capacity[887].

vi.) The engine speed control is achieved by variation of the supply of the air/fuel mixture. Therefore, the fuel system must provide for efficient fuel flow regulation mechanism.

11.8.1.2. Conversion of Diesel Engine to Dual-Fuel Engine

The world had 27,765,376 natural gas vehicles using engines running on natural gas as compression ignition or spark ignition engine modes by 31st July 2019. The compression ignition natural gas engines are more popular because of their higher reliability and fuel efficiency compared to the conventional engines [113, 284, 446]. In the conversion of a diesel engine to dual engine, the main engine components and systems that should be modified include the fuel system, its fuel injection system, the exhaust gas system, air intake or charging system, the combustion chamber, and engine control System while the air fuel ration has to be reduced [275, 496, 558, 890]. About the engine performance, the efficiency generally varies with the power required for gas compression. The more the compression power requirement, the less the engine overall efficiency.

In a study at the gas powered Ringgold Cogen power station, the plant heat rate was about 9300 kJ/kWh which corresponds to an efficiency of around 39% with plant availability of about 90.1% observed over five years of operation [891]. In this plant, the diesel engines ran on natural gas compressed to 250 bars. The injection was with pilot oil amount of about 5% of total fuel intake was applied. The Ringgold Cogen Power plant has average specific

lubricating oil consumption was about 0.8 g/kWh [93, 892]. The main limitation with gas engines is higher NO_x emissions compared to 100% diesel engine fuel mode. As a control measure, a catalytic exhaust purification system may be recommended to reduce NO_x emissions from a realized level of 1300 mg/MJ(fuel) to a desirable level of 200 mg/MJ or less as in a case of existing natural gas power plant in Finland [892].

A diesel engine can be converted to a full gas engine reducing the compression ratio and introducing a spark ignition system. The design compression ratio a diesel engine is too high if converted to spark ignition operation and will introduce engine knocks, hence the need to reduce the compression ratio[889]. This is because high pressure will cause too high temperature in the cylinder enough to pre-ignite the fuel causing knocking[887].

The conversion of diesel engine to dual-fuel engine that uses both natural gas and diesel in this study involves the following proposed modifications to the diesel engines in Kipevu III power station.

i.) Introduction of Dual-Fuel Electronic Control Unit (ECU).

The role of the ECU is to send high speed pulse-modulated signals to natural gas and diesel fuel injectors and hence control amount of fuel injected. This control unit determines and regulates the supply of dual fuel to the engine ensuring optimum fuel control which is usually 8% diesel combined with 92% natural gas under steady state conditions[893].

ii.) Turbo-Charger Air Bypass (TAB).

This controls the amount of air provided by the turbocharger by use of bypass valve usually of a butterfly design. However, other effective valves can still be used.

iii.) Pistons and Combustion Chamber Modification

The overall objective is to change the compression ratio and are redesigned the combustion chamber to influence combustion characteristics including flame flow. The piston groove may be modified as well as the bowl while the length of the connecting rod may also need modification[894].

The conversion to compressed natural gas (CNG) for CIE (compression ignition engines) leads to better engine performance with reduction in engine emissions which are mainly in the form of nitrogen oxides (NO_x), (HC) hydrocarbons, and carbon dioxide (CO₂)[893]. However, other studies have shown that the use of CNG diesel engines ultimately leads to an increase in NO_x emissions in the engine exhaust [895]. In another study, a performance

analysis was done for a diesel-CNG (dual fuel) engine of specifications 2.5-liter (cm^3) cylinder with 4-cylinders with a common rail direct injection diesel engine. The engine performance and exhaust gas emissions of several diesel-CNG dual fuel blend ratios, i.e., 100:0, 90:10, 80:20, 70:30, 60:40 and 50:50 was analysed for performance. The study results showed that for engine loading of 100%, 75%, 50%, the engine brake torque and brake power for a dual fuel engine at a speed between 2000 and 3000 rpm was higher compared with 100% diesel only engine mode[895]. However, it was at 50:50 diesel-CNG ratio that the highest brake torque and brake power were achieved. However, these was achieved with highest brake specific fuel consumption, implying that more fuel was consumed per unit brake power output[59, 632, 893].

11.8.2.Materials and Methods

This study targeted the largest diesel power plant in East and Central Africa, namely Kipevu III 120 MW power plant which is equipped with 7 Wärtsilä W18V46 of capacity 17.1 MW running on heavy fuel oil. The engine specifications are specified in Table 11-7.

Table 11-7: Engine Technical Specifications [896].

	Parameter	Specifications
1	Configuration	V-Engine
2	Number of Cylinders	18
3	Cylinder bore	460 mm
4	Stroke	500 mm
5	Speed	500 rpm
6	Mean piston speed	9.67 m/s
7	Mean Effective Pressure	24.3 Bar
9	Swept Volume per cylinder	96.4 dm^3
10	Number of Inlet Valves	2 Per cylinder
11	Number of outlet Valves	2 per Cylinder

12	Direction of Rotation	Clockwise
13	Engine Length	13.580 m
14	Width	5.347 m
15	Height	5.488 m
16	Weight	237,000 Kg

From Table 11-7 it is established that the power plant has got seven V-engines of weight 237 tones and run at a constant 500 revolutions per minute (RPM).

11.8.3.Methods and Procedure

For a successful conversion of a diesel engine power plant to a dual-fuel natural gas the following procedure is applied:

- i. Obtain existing design specifications of the diesel engine.
- ii. Modification and addition of parts of the engine.
- iii. Reduction of the compression ratio.
- iv. Identify the appropriate gas storage and gas supply system.
- v. Draw a layout design of the Dual-Fuel Power Plant.

11.8.4.Overview of the Design

In the design of a dual-fuel engine power plant, the following modifications and additions need to be done on the existing diesel power plant. For successful conversion of the injection system, a D-GID® Electronic Control Unit is proposed for introduction before the natural gas and diesel are supplied to the combustion chamber or the cylinder. This system is the first technological platform developed by Ecomotive Solutions. The control unit allows proper and adequate mixing of the fuel based on the engine condition and loading requirements. D-GID® Control Unit helps determine the correct amount of diesel fuel injected and air/gas mixture dosage dynamically, modifying it in real time based on determined engine performance need [1, 100, 888, 897]. The overall performance of a converted engine is a function of the load conditions, fuel mixture homogeneity, and combustion chamber design which affect flame speed, fuel mixing and combustion efficiency [898, 899].

11.8.5.Reduction of the Compression Ratio

The use of natural gas as a fuel for diesel engines requires a lower compression ratio (CR) as compared to pure diesel fuel. Therefore, the engine design must be modified to achieve a lower compression ratio [894]. This can be realized by adding a plate between the piston head and the engine cylinder block, just like a seal between the engine block and the piston head to increase the clearance volume between the piston top dead center (TDC) and the cylinder head. The plate shape should be similar to the shape of the top face of the engine piston head [897]. The plate is added in a form of a gasket plate which normally exists for all engine blocks and acts as a seal between the piston head and the engine block. In the cylinder assembly, a gasket is placed between the top of the engine block and piston acts as a seal between the piston head and the engine block [897, 900]. Figure 11-7 demonstrates the location of the extra plate to added in the modification.

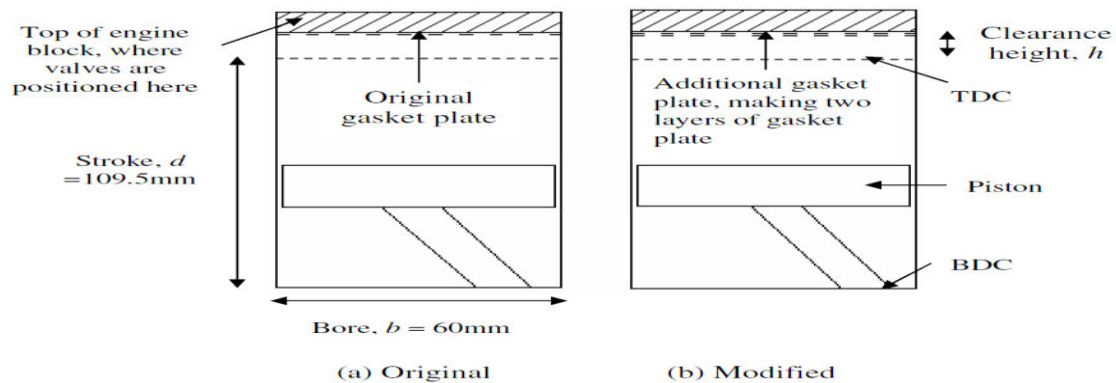


Figure 11-7: Additional Plate to Increase Clearance Volume [900].

Figure 11-7 demonstrates the proposed modifications for the combustion chamber aimed at reducing the compression ratio of the diesel engine. Introduction of an additional gasket effectively reduces the clearance volume along the cylinder axis leading to lower compression ratio as demonstrated by the relationship between compression ratio (CR), clearance volume (V_c) and swept volume (V_s) of the engine shown below.

For one cylinder:

$$\text{Swept volume } V_s = \frac{\pi \times b^2 \times l}{4}$$

b- bore diameter.

l- stroke length

V_c - Clearance volume

$$\text{Compression ratio C. R} = \frac{V_s + V_c}{V_c}$$

Additional plate creates an extra volume V_{plate}

$$V_{\text{plate}} = \frac{\pi}{4} \times b^2 \times t$$

Where t – plate thickness

$$\text{The new C. R} = \frac{V_s + V_c + V_{\text{plate}}}{V_c + V_{\text{plate}}}$$

11.8.6. Gas Piping and Supply System

A gas supply system is required to supply natural gas from storage tank to the dual-fuel engine [886, 897, 901]. It includes: an industrial gas filter, a pressure regulator, a gas shut-off valve and pipes.

11.8.6.1. Gas Storage System

Natural gas is typically stored in underground or above ground based on quantities, state, and application. Where the gas is stored above the ground, specially fabricated tanks that limit access is used. Transportable or mobile tanks can also be used for natural gas storage purpose. This system makes loading and transportation easy and cheaper in many applications[445]. Natural gas can be stored as CNG (Compressed Natural Gas) or LNG (Liquefied Natural Gas). LNG takes up about 1/600th the volume of natural gas in the gaseous state. The natural gas liquefaction process involves removal of certain undesirable components, such as dust, acid gases, helium, water, and heavy hydrocarbons. The natural gas is then condensed upon cooling to form a liquid[1, 22, 23, 33, 100, 888]. This is at approximately -162°C and maximum pressure about 25kPa. The choice of the storage facilities depends on the consumption rate of the fuel. For large volumes of natural gas, it is easier and convenient to store natural gas in liquid state. Extra equipment is needed for the process of regasification of LNG, which converts LNG from liquid state to gaseous state before use. This needs a heat exchanger using ambient air or sea water as the source of heat. Other required equipment includes an LNG pump, vaporizer, and a compressor. On the other hand, in selecting CNG tanks, the most important parameter is the storage pressure for the natural gas[445, 446].

11.8.7. Conversion of Injection System

The conversion requires modification of the fuel the injection system to handle both natural gas and diesel fuel for the dual fuel engines. In this study, a D-GID® Electronic Control Unit is proposed for installation at a suitable location just before the natural gas and diesel are injected into the engine. The D-GID® system was a development of Ecomotive Solutions. The system will facilitate the injection of both diesel oil and natural gas in form of CNG, liquefied natural gas (LNG), Syngas, bio-methane, and other gases to the engine cylinder. The D-GID® Control Unit is used to determine the quantity of diesel oil and natural gas to be injected in real time basis depending on engine load conditions and requirements [902, 903]. Figure 11-8 illustrates the new injection system to facilitate dual fuel operation of the power plant engines.

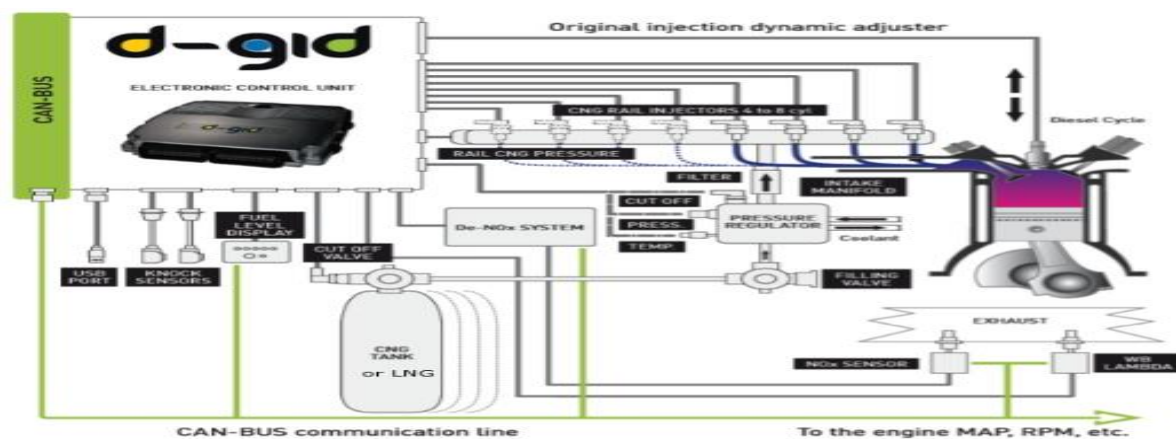


Figure 11-8: D-gid® electronic control unit injection system [902, 903].

Figure 11-8 illustrates the injection system for the proposed dual fuel system with related elements like the CAN-BUS systems, LNG storage and injection dynamic adjuster.

The control system manages and controls the quantity of diesel fuel injected, which can be reduced by as high 80-90% during steady state conditions. However, the average diesel oil substitution rate under dynamic load conditions is generally 40-50%. The D-GID® ECU manipulates the fuel ratios to maintain engine proper performance under dual fuel mode.

10.3.11. Converted system.

Figure 11-9 illustrates the proposed dual diesel-CNG system for conversion of the diesel power plant to dual fuel power plant.

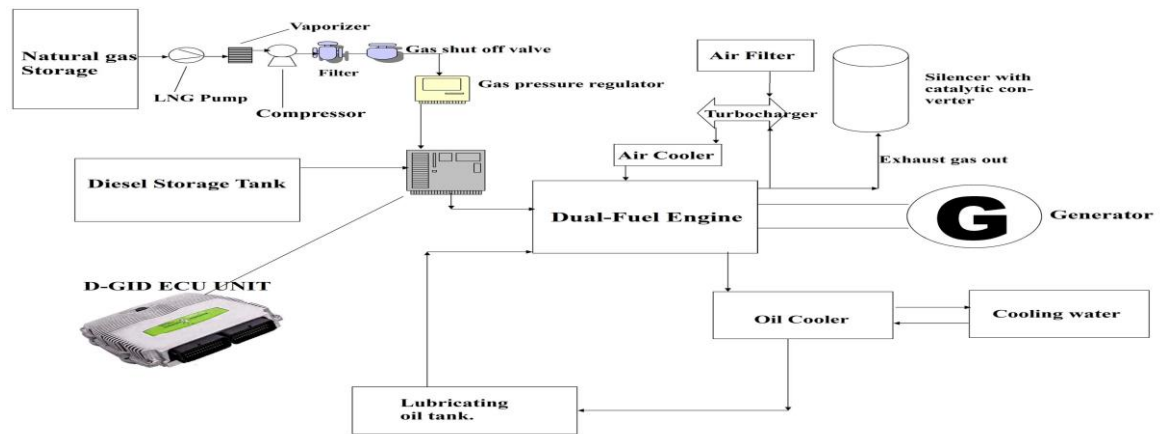


Figure 11-9: The Dual fuel system mode.

From Figure 11-9, the main elements of the proposed system are the D-Gid ECU unit, natural gas storage and handling facilities, and engine prime mover with all the necessary systems charge air system, fuel system, generator, engine units, and cooling system.

11.8.8.Results and Discussion

Various engine operating parameters must be modified for the diesel engines to run on natural gas. The parameters before and after conversion are shown in Table 11-8.

Table 11-8:Parameters before and after conversion.

Parameter	Before Conversion	After Conversion
Compression ratio	22:1	17.1
Specific fuel consumption (kg/h)	3400	2878.72
Fuel cost per hour (KES/hr)	186,190.474	134,164.12
Load factor	0.5	0.5
Cost of fuel per kWh (KES/kWh)	10.95	7.89

From Table 11-8, it is noted that the conversion involves reduced compression ratio from 22:1 to 12:1, the specific fuel consumption reduced by 39.1% and fuel cost per unit reduced by 27.9% while load factor was maintained at 0.5 for the purpose of performance analysis.

11.8.8.1. Cost Analysis

Table 11-9 informs the cost analysis while Figure 11-10 depicts the payback period when the fuel savings and time are considered.

Table 11-9: Cost Analysis Table.

Item	Cost (KES)
Total Cost of Investment	153,492,500.00
Annual Fuel Cost Savings	453,407,867.60
Payback Period	4.06 Months

From Table 11-9 it is noted that the annual cost of savings is higher than the cost of investment meaning that the payback period is less than a year, i.e. 4.06 months. Figure 11-10 demonstrates payback period from fuel savings.

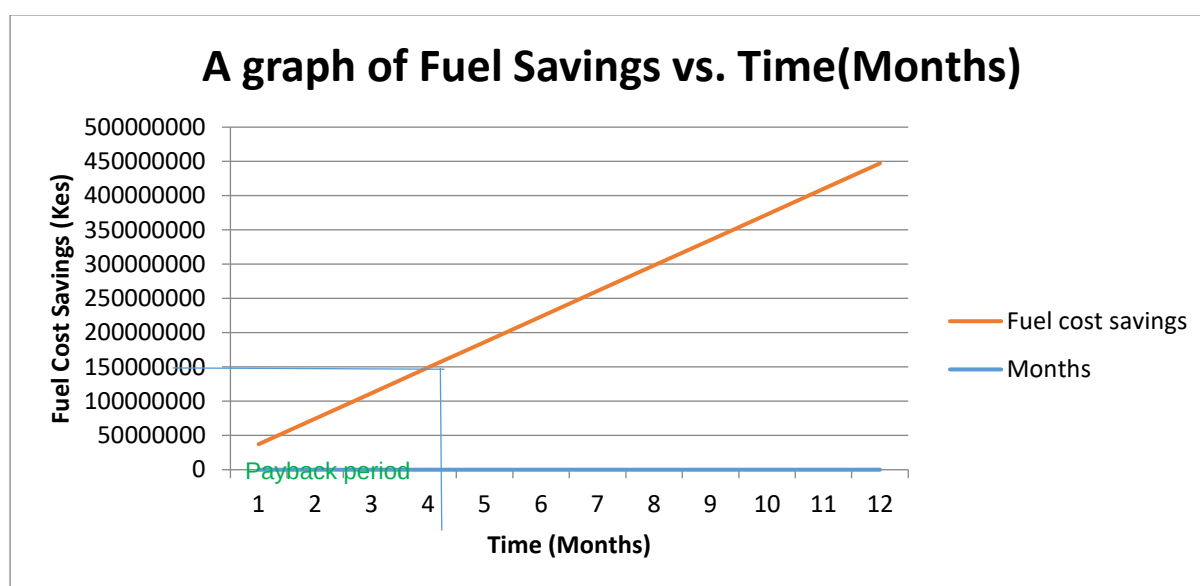


Figure 11-10: A graph of Fuel Savings vs. Time (Months).

Figure 11-10 shows a graph of cumulative fuel cost savings against period in months with the payback being about 4.06 months. This is very encouraging and attractive payback period for potential investors and financiers.

11.8.8.2. Discussion

The Wartsila W18V46 engines used in the power plant have a compression ratio of 22:1 is ideal for use with diesel and heavy fuel oil. For this engine to run on natural gas and diesel, the compression ratio must be reduced by increasing the engine cylinder clearance volume. Two thicknesses of 10mm and 5mm are used for analysis, which give compression ratios of 13.4 and 17.1, respectively. For a dual-fuel engine, a compression ratio of 16-18 is required. Therefore, the 5mm thickness is chosen for these engines. The specific fuel consumption (sfc) of Kipevu III is 3400 kg/h. From this sfc, for one engine unit the cost of diesel fuel is calculated per hour. A diesel to natural gas ratio of 1:4 is chosen in our conversion. This ratio reduces the amount of diesel fuel used significantly and replacing it with natural gas. Natural gas has a higher calorific value of 52,000 kJ/kg compared to diesel 42,000 kJ/kg, which means it takes less natural gas to produce same power with diesel.

Using the diesel to natural gas ratio and the specific fuel consumption (sfc), the volume of diesel consumed after conversion is calculated and using the prevailing average cost of diesel per Liter, the cost of diesel fuel (after conversion) is determined. For natural gas, the consumption and cost of natural gas is used to determine costs involved. Therefore, very important for analysis of both fuels is the ratios and their calorific value which helps in quantifying consumption in form of, the mass of natural gas consumed is calculated and the diesel oil used. The total cost of the dual fuel is calculated based on diesel cost of KES 46/liter (US\$0.46/liter) of oil and natural gas cost of \$605/ton. Using a diesel/natural gas ratio of 1:4, the diesel sfc reduces to 640kg/h from 3400kg/h and the sfc of natural gas is 2196.72kg/h. The total sfc reduces to 2,836.72kg/h of natural gas based on the analytical calorific value of 52,000 kJ/kg of natural gas with average cost of natural gas taken as \$605/ton. This fuel combination leads to lower cost of the dual fuel compared to the cost of diesel oil when used alone. For the 7 engines, a total of KES 453,407,867.60 (US\$ 4,534,079.00) in savings at average load factor of 0.5 is realized. Considering all the additions to the existing design and all costs incurred during conversion, the total direct cost of investment amounts to KES 153,492,500.00 (US\$ 1, 534,925.00). The actual project cost is expected to be more than this value.

Based on the total annual fuel cost savings and the cost of investment, the payback period for the whole project is estimated at 4.06 months. This payback looks too short and too attractive, but the analysis is based on prevailing price of oil and natural gas not actual costs which must capture the indirect costs like handling, transport, and storage costs as well as initial capital

investment costs which will have a bearing on total cost of the conversion as well as the cost of system operation and maintenance.

The conversion requires provision for natural gas storage facilities and supply system which were introduced in the proposed design modification. The dual fuel mode proposes a diesel/natural gas ratio of 1:4, which reduced the diesel specific fuel consumption by 81.2% with natural gas consumption of 2196.72 kg/h. These fuel savings will influence renegotiation of the power purchase agreement resulting into lower tariffs, higher load factor and power plant utilization which translates to more revenue and reduced unit cost of power with lower environmental impact as well as better return on investment from the largest grid connected diesel power plant in East and Central Africa.

11.8.9. Conclusion

Natural gas–diesel dual fuel engine operation is an important pathway in the reduction of diesel engine related emissions like carbon dioxide (CO₂) and particulate matter (PM), and sulphur dioxide emissions while maintaining the efficiency and reliability associated with use of diesel engines in power generation. As a result of commitments set by many countries to the Paris Agreement, the demand for low carbon and renewable fuels for internal combustion engines is high globally creating demand for natural gas which can as well be produced from renewable sources. It is however argued that the shift will delay the transition to 100% renewable sources of energy if we have renewed demand for natural gas from fossil fuel sources.

This study showed that a dual fuel diesel power plant running on both natural gas and diesel has better power plant performance indicators in terms of engine specific fuel consumption, engine brake thermal efficiency, diesel engine indicated thermal efficiency, the power plant electricity generating unit cost of power, the total engine emissions and hence leading to less environmental impact. Therefore, the engine fuel conversion will reduce the cost of electricity generation and amount of pollutants associated with diesel in power generation. The conversion will also lead to better return on investment of the plant because of reduction in fuel related costs and overall unit cost of power. Conversion from diesel fuel powered engines to full gas and dual fuel mode is both technically and financially feasible.

The proposed partial conversion to dual fuel mode is faster, cheaper, and more feasible as it requires less modifications and allows for more fuel diversity and flexibility in the diesel power plant operation and maintenance. Modification of the injection system proposed

involved introduction of an electronic unit for control of the amount and ratios of diesel and natural gas injected for combustion while compression ratio was also reduced to cope with new fuel characteristics. The conversion will reduce specific fuel consumption that can lead to cheaper power and more generation and revenue for investors from more electricity sales. This in turn will be reflected in reduced electricity bills for the consumers. Therefore, conversion from pure diesel to dual fuel diesel engine power plants is a sustainable way of generating electricity for sustained economic growth and development in a cleaner environment as a measure in the energy transition to low carbon and renewable sources of energy.

11.8.10. Recommendations

Upon successful conversion of Kipevu III to a dual fuel plant, it is recommended to carry out a feasibility of total conversion of the power plant to a full gas power plant. With the average load factor of the power plant being just 0.5, about 50% of the total capacity remains unutilized. This is mainly due to high cost of power hence the need to cushion consumers from high electricity bills due to the diesel power plants. Therefore, conversion to dual fuel will reduce cost and increase power plant demand leading to higher load factor and power plant utilization which translates to higher revenue and efficiency of operations and thus reduction in unit cost of power. Since the research targeted Kipevu III power station alone, it is recommended that similar studies be carried out for other diesel power plants to facilitate a possible industry wide policy shift and conversions to gas as a fuel.

11.9. Design and Analysis Dual Cycle System for a 60 MW Diesel Engine Power Plant

The content of this section is published in paper [114] co-authored by Prof. Oludolapo. In this study, that targeted a 60 MW Kipevu 1 power station in Kenya, a dual cycle power plant is proposed by developing a Rankine cycle-based cogeneration plant to utilize excess energy is for generation of extra electricity using a steam turbine running on steam produced from heat recovered from exhaust heat. The study demonstrated large potential of energy savings from diesel engine power plants and to this effect Kipevu I can be able to recover about 5.2 MW of power from the flue gases according to our design analysis. Recovery of waste heat from exhaust gases improves efficiency and reduces emissions the plant per unit power produced and create extra revenue for the power plant. An engine converts just 30 to 40% of energy in fuel to useful power with the rest being lost in the cooling and exhaust systems. The

main power plant elements include heat exchanger, the boiler (with feed pump, economizer, super heater, and preheater), the steam turbine and the turbogenerator. In the proposed development an exhaust gas boiler is used to generate steam using exhaust heat, the wet steam is superheated in a superheater heater at a mass flowrate of 2.8 kg/s and then used to run a steam turbine for extra power generation from a generator that is coupled to the steam turbine.

11.9.1.Introduction

Since engines convert less than 40% of fuel power to useful work, over 60% of the energy in fuel is lost through the exhaust and cooling systems. Through waste heat recovery technology, the low-grade heat in the cooling system can be recovered effectively with the organic Rankine cycle[330, 870]. Generally, an internal combustion engine releases 30-40% of the fuel energy from combustion through the exhaust to the environment and an almost equal amount through the engine coolant (Wilson John M. R., et al., 2017). This energy is just sufficient for recovery and for use in many thermal applications with minimal heat losses in the designed waste heat recovery system[330, 870, 904]. Industrial Power plants and heat engines in general, waste up to more than half its available energy in form of heat[905].With a suitable CHP system, excess heat that would normally be wasted can be captured and converted into electricity. By converting this excess energy into useful power, we can achieve efficiencies as high as 89 %. This in turn means there is less fuel needed to run the plant engine, thus by making it so, then there is less pollution produced to the environment. While cogeneration has been used in power plants for a while now, we will discuss a provision of the same in the Kipevu-1 power station Combined heat and power (CHP) systems in both power stations and large plants are becoming one of the most important tools for reducing energy requirements and consequently the overall carbon footprint of fundamental industrial activities[518]. While power stations employ topping cycles where the heat rejected from the cycle is supplied to domestic and industrial consumers, the plants that produce surplus heat can utilize bottoming cycles to generate electrical power.

The overall objective of the study was to design a diesel engine Rankine cycle-based cogeneration system for the 60 MW Kipevu-1 power plant. The specific objectives were to carry out a performance analysis of Kipevu-1 power station and propose measures to convert it to a dual cycle power plant working on both a diesel engine cycle for engines and Rankine cycle from steam generated from engine exhaust heat.

Through cogeneration technology total fuel consumption and related greenhouse gas (GHG) emissions can be reduced by generating both electricity and useful heat from the same fuel input. Cogeneration is a form of local or distributed generation as heat and power production take place at or near the point of consumption. For the same output of useful energy, cogeneration uses far less fuel than the traditional separate heat and power production, which means lower greenhouse gas (GHG) emissions as fossil fuel use is reduced. The advantage of the combined production of heat and power results from the more efficient use of fuel, and corresponding reductions in the emissions of SO₂, NO_x and CO₂. [101, 206, 226].

11.9.2. Research Materials and Methods

This study targeted the first grid connected diesel power plant, known as Kipevu I Power Station that utilizes Heavy Fuel Oil (HFO) as the primary fuel, in addition to industrial diesel oil (IDO) which is used for starting and stopping of the diesel engines. Kipevu I thermal power station which was constructed through project procurement between the government of Kenya and Japan, commenced its commercial operations in December 1999 and has been operating satisfactorily. The plant has Six medium-speed generator units, each with an installed capacity of 12,500kW (total capacity of 75MW) but an effective capacity of 10,460Kw. However, one of these engine units has undergone total failure and thus declared obsolete. The power station is owned and operated by the Kenya Electricity Generating Company Ltd. (KenGen) and currently still operating. [906].

Exhaust gases leaving internal combustion chambers of I.C engines are at very high temperatures approximating to about 450-600°C. These gases have high heat content, carried away as exhaust heat emissions. These waste gases carrying such high contents of heat are released to the environment only to harmful disposal. The recovery and utilization of the exhaust heat will not only increase capacity of power generation but also improve combustion process efficiency as well as ensuring reduced pollution. Furthermore, cogeneration in diesel plants will help lower the unit power cost which is currently very high. Employing the topping cycle, heat is produced when fuel is used to generate electricity which is then recovered. The recovered waste heat is thus passed through a series of Heat Recovery Steam Generators (HRSGs) to generate steam which is utilized to run steam turbines for power regeneration [21, 685, 781].

11.9.3.Engine Design

The power plant has six (6) diesel engines with nominal capacity of 10.460 MW whose specifications are as shown in Table 11-10.

Table 11-10: Kipevu I Engine specifications (Author's summary).

Parameter	Quantity/Type
Engine Manufacturer	MAN - B & W
Engine capacity	10460kW
Type of the Engines installed	9 cylinder-inline-4 strokes
No. of Cylinders (n)	9
Bore diameter (d)	580mm
Stroke Length (L)	640mm
Engine Speed (N)	428 RPM
Compression ratio (r)	13.2
Specific Fuel Consumption	0.178kg/kWh
Swept volume capacity	1521800cc
Ignition Pressure (IP)	23.1 bar
Compression pressure	135 bars
Mean Piston Speed	9.1m/s
Sense of rotation	Anticlockwise
Cooling system	Water cooled
Mean Torque (T)-Calculated	233.37 kNm

From Table 11-10, it is noted that the engines 9-cylinder inline engines operate at a synchronous speed of 428 rpm.

11.9.3.1. Design Procedure

Analyze the quantity of heat lost through exhaust gases at the appropriate points. Then identify the appropriate interfaces and interconnections as follows.

- i.) Heat regenerator (interface I)
- ii.) Exhaust Gas Boiler (interface II)
- iii.) Steam Turbine (Interface III)
- iv.) Steam Turbine Generator (STG)
- v.) All appropriate sizes and types of piping systems
- vi.) All flow points of water, exhaust gases, steam, and power

This was followed by the design, specify, and select appropriately each of the required interface and interconnections. Next was to observe all necessary design considerations providing the appropriate allowances for optimum conditions.

11.9.3.2. Overview of the System Design

Designing a cogeneration plant requires selection of the most economic combination of equipment from among the many options available [907, 908]. The technology is usually chosen based on the energy forms required by the user and may include a conventional boiler, the prime mover, heat regenerators and combustion turbines[909]. Two technical factors that play an important role in determining the plant configuration are the available fuel and the ratio of heat demand to power demand. Figure 1 below shows the proposed structure of the cogeneration plant[904]. Figure 11-11 demonstrates the proposed configuration of the cogeneration plant.

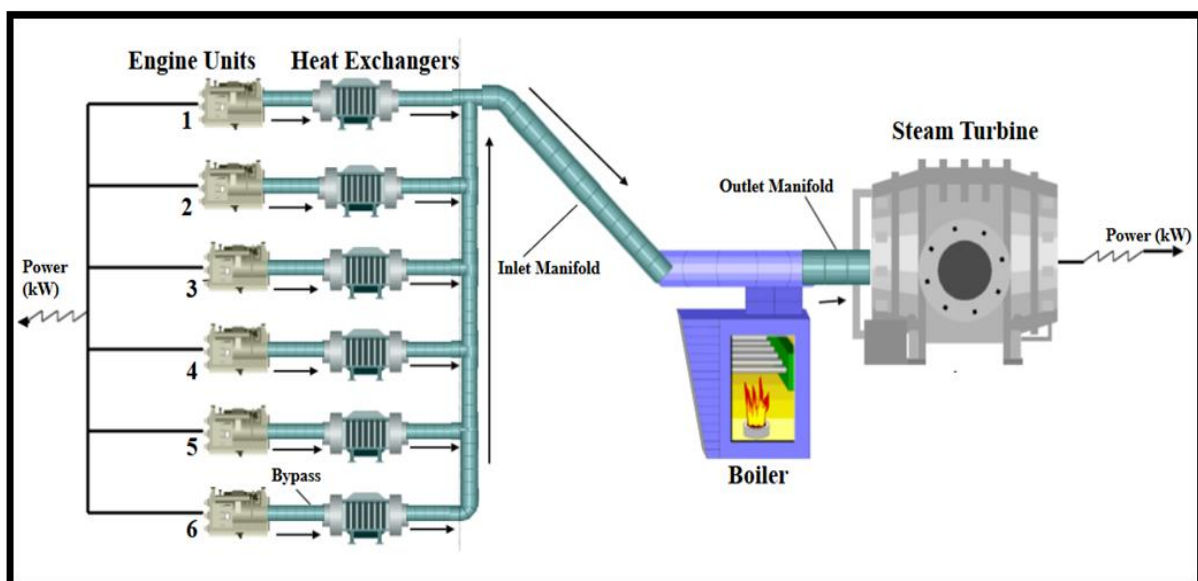


Figure 11-11: The system proposed design overview. (Author's proposition)

Figure 11-11 shows the main elements of the proposed system being exhaust system from the six engines connected to a common duct that leads the combined exhaust to an exhaust gas boiler.

11.9.3.3. Engine Performance Analysis

i.) Indicated power.

$$I.P = \frac{P_{me} \times L \times A \times N \times k}{60 \times 2} = 12,538.4212 kW$$

ii.) Brake power (B.P)

$$B.P = \frac{2 \pi N T}{60} = 10459.46 kW$$

iii.) Mechanical efficiency

$$\eta_m = \frac{B.P}{I.P} \times 100\% = 83.4\%$$

iv.) Mass flow rate of the exhaust gases,

$$m_e = m_f + m_a = 0.5172 + 5.7 = 6.2172 kg/s$$

v.) Heat loss by exhaust gases.

$$\begin{aligned} Q_e &= m_e \times C_p \times \Delta T \\ &= m_e \times C_p \times (T_{source} - T_{sink}) \\ &= 6.2172 kg/s \times 1.008 KJ/kgK \times (310 - 170) ^\circ C \\ &= 1040.3116 Kw \end{aligned}$$

11.9.4. Preliminary Design

11.9.4.1. Heat Exchanger Design

Figure 11-12 shows the design overview of a counterflow heat exchanger.

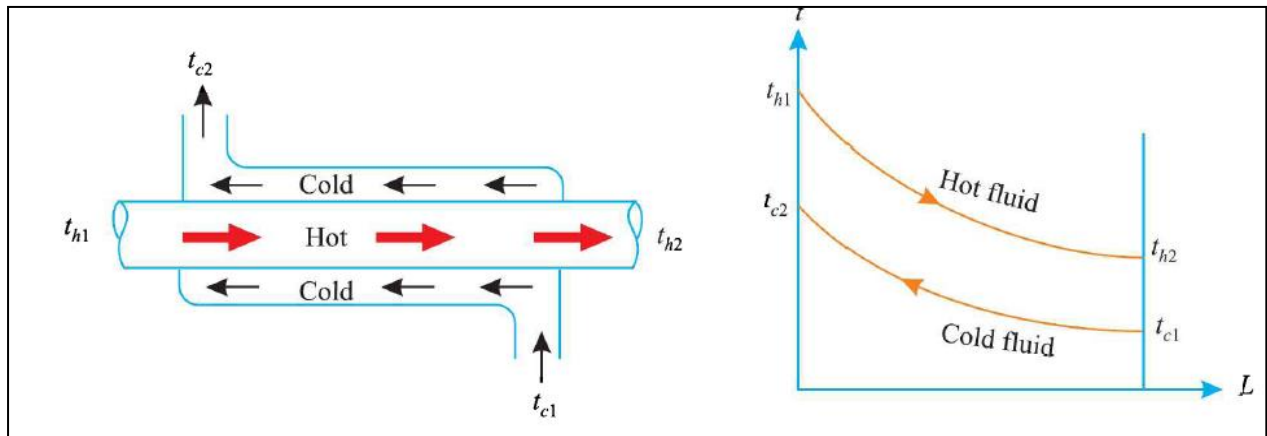


Figure 11-12: Exchanger flow arrangement (Author's conception)

Figure 11-12 shows a counterflow heat exchanger design to be used in the design of the cogeneration plant exhaust gas boiler and superheater tubes. The flue gases and the water/steam in tubes flow in opposite directions, hence counter flow heat exchangers. t_{c2} and t_{c1} are the outlet and inlet flue gas temperatures while t_{h1} and t_{h2} is the temperature of water at inlet and outlet. The flue gas occupies the shell side while water occupies or flows in tubes.

11.9.4.2. Heat Transfer Area and Number of Tubes

- i.) U-tube construction exchanger
- ii.) 1-shell and 2-tube pass heat exchanger ($N_p = 2$)
- iii.) Outer tube diameter ($d_o = 25.4\text{mm}$ (1 in),
- iv.) tube thickness $t_o = 2.108\text{mm}$ (0.083in)
- v.) Inner tube diameter $d_i = 21.184\text{mm}$ (0.834in)
- vi.) Pitch $P_t = 1.25d_o = 1.25 \times 25.4 = 31.75\text{mm}$, square pitch layout
- vii.) Let length of tubes (L_t) be 4.0m

Figure 11-13 shows the proposed assembly of the shell and tubes with baffle plates in the proposed heat exchanger assembly.

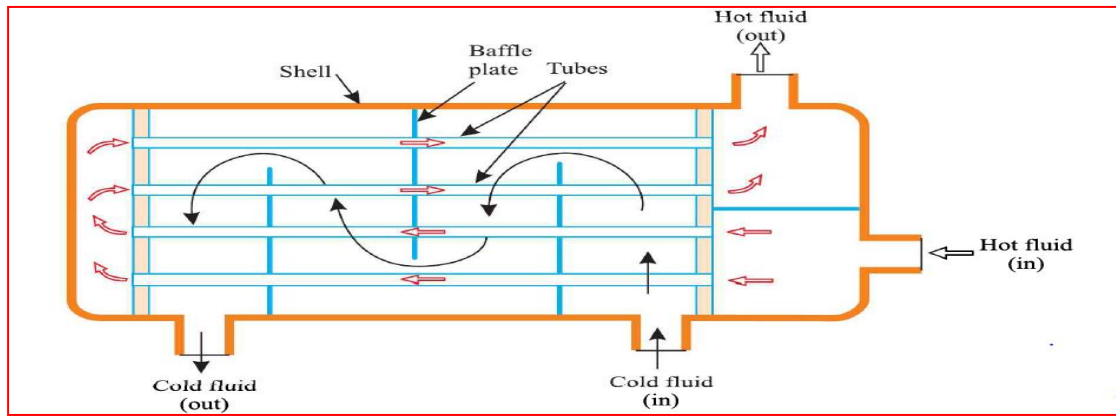


Figure 11-13: Heat exchanger flow arrangement (Author's design)

From Figure 11-13, it is noted that the main parts of the heat exchanger for exhaust heat recovery are the shell, tubes, and baffles which must be designed for size, strength, and materials.

$$A = \frac{\dot{m}_e C_{Pe} (T_{ei} - T_{eo})}{U_o \Delta T_{lm} F_T} = \frac{6.2127 \times 1.0295 \times 10^3 (310 - 170)}{60 \times 175.498 \times 0.95} = 89.513 m^2$$

i. Shell diameter, D_s

For the 1-shell and 2-pass heat exchanger, for number of tubes being 280, the minimum recommended shell diameter is 84 inches.

$$D_s = 84 \text{ inches} = 84 \times 25.4 \text{ mm} = 2133.6 \text{ mm}$$

ii. Baffle spacing and baffle plates design.

According to TEMA Standards, the recommended baffle spacing is $[0.4D_s \text{ to } 0.6D_s]$

$$\text{Baffle spacing} = 0.5D_s = 0.5 \times 2133.6 \text{ mm} = 1066.8 \text{ mm}$$

The proposed heat exchanger configuration is shown in Figure 11-14.

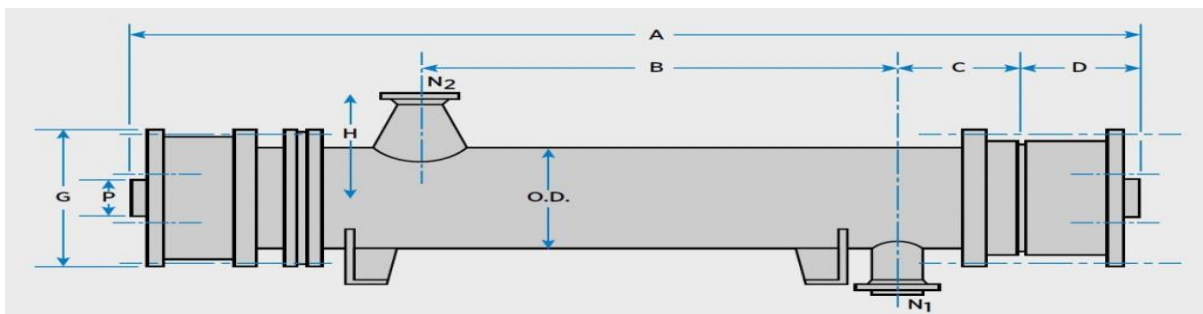


Figure 11-14: Heat exchanger configuration plan view (Author's sketch).

Figure 11-14 shows the overall dimensions for the proposed shell tube heat exchanger assemble where OD is outer diameter, A is overall length and B is the spacing between the two axes of the coolant inlet and outlet.

iii. Shell thickness

$$t_s = \frac{PR_s}{\sigma_j - 0.6P} + \text{Corrosion allowance}; j \text{ is efficiency of the joint}$$

$$t_s = 2.9385\text{mm} + 1.5\text{mm}$$

$$= 4.4385\text{mm}$$

Figure 11-15 is an illustration of the proposed heat exchanger assembly.

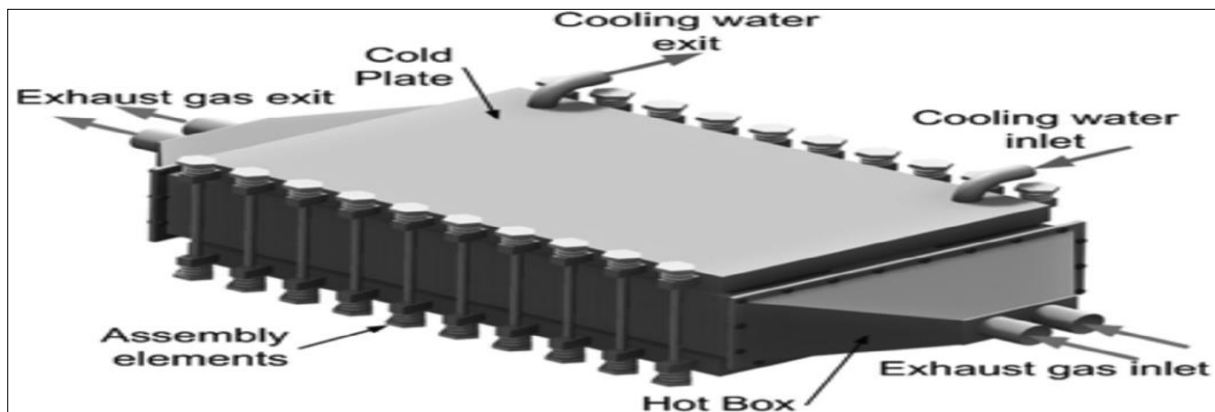


Figure 11-15: Exchanger components (Author's illustration)

Figure 11-15 is a 3D illustration of the heat exchanger assembly. The main elements being exhaust gas inlet and outlet, assemble elements, water coolant inlet and outlet for the proposed development.

11.9.4.3. The Exhaust Gas Boiler Specification

- Pipe Grade: ANSI SCH 40
- Boiler cylinder volume 729L
- Pipe Size: NPSI ¼
- Desired Steam pressure :40bar
- Desired flow rate of steam $v = 0.00987\text{m}^3/\text{s}$
- Density of steam, $\rho_{\text{steam}} = 2.25\text{kg}/\text{m}^3$
- Mass flow rate of steam , $m = v \times \rho_{\text{steam}}$

$$= 0.00987 \text{ m}^3/\text{s} \times 2.25 \text{ kg/m}^3$$

$$= 0.0222075 \text{ kg/s}$$

$$= 79.947 \text{ kg/hr}$$

The main components of the exhaust gas recovery system are summarised in Figure 11-16.

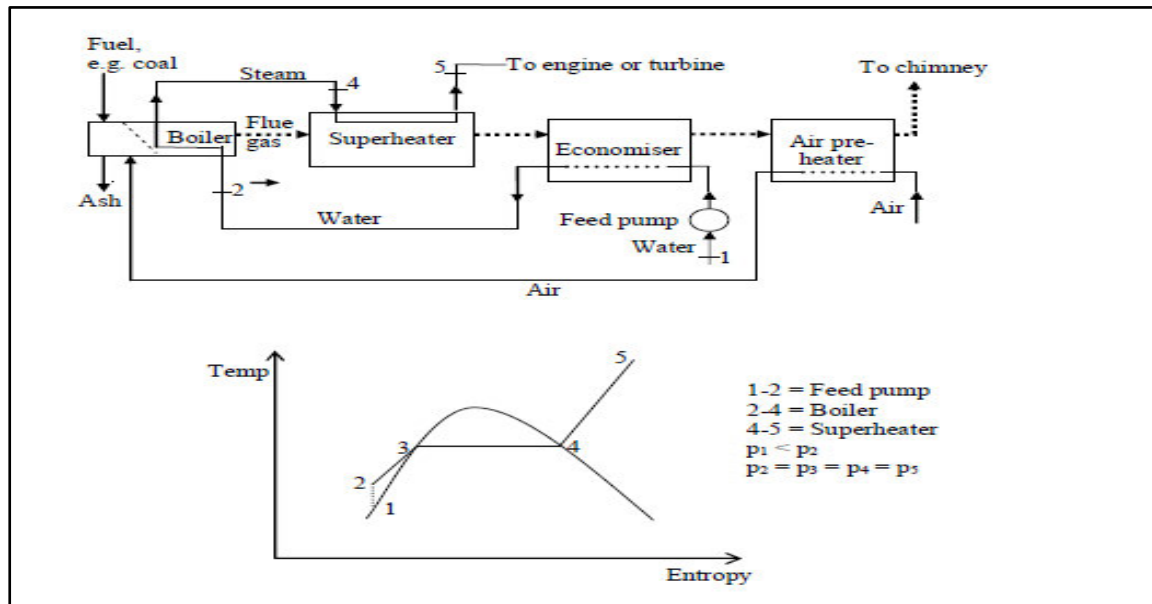


Figure 11-16: Exhaust gas boiler components (Author's work)

Figure 11-16 shows the Rankine cycle on a TS diagram for the proposed cogeneration powerplant. It shows that steam is superheated after generation in the exhaust gas boiler.

11.9.4.4. The Steam Turbine Design

The specifications of proposed steam turbine are.

- i.) Steam velocity exiting the nozzle=300,000 rpm
- ii.) Tangential component of velocity out of nozzle is twice the blade speed.
- iii.) Tangential component of absolute velocity out of rotor is zero,
- iv.) High head of about 120m since it's an impulse turbine.
- v.) Mass flow rate of steam, 1kg/s (unit)

$$U = \omega Rm$$

$$\frac{300,000 \times 2\pi \times \frac{0.42672 + 0.33858}{2}}{60} = 120.213 \text{ m/s}$$

The turbine rotor is the moving part of the steam turbine. Figure 11-17 illustrates the steam turbine rotor assembly

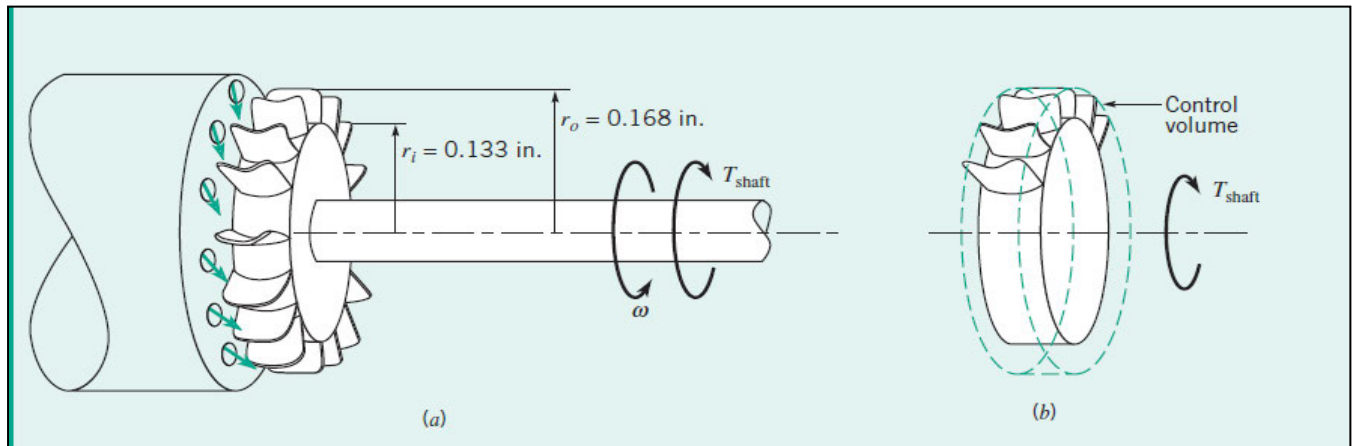


Figure 11-17: Steam turbine rotor orientation

Figure 11-17 shows the overall dimensions of the turbine rotor shaft assembly where r_o is the overall radius over the turbine blade tips.

11.9.4.5. Steam Turbine Selection Criteria

The guidelines in Table 11-11 are used in the selection of an appropriate steam turbine.

Table 11-11: Summary of our selected Steam Turbine Attributes for CHP

Size range	From the available wattage ratings, our STG will expend a capacity of 10MW.
Thermal output	This being a CHP configuration, it shall use backpressure or (extraction steam) turbines to generate power and thermal energy. Backpressure steam turbines produce low pressure steam while extraction turbines deliver both low pressure and medium pressure steam.
Part-load operation	Steam turbines have relatively good part-load performance, but efficiency does decline as power output is reduced.
Fuel	A steam boiler shall be used to generate steam required for the steam turbine generator. Our boiler will utilize industrial HFO as the main source of fuel.
Reliability	Steam turbines are a mature technology with excellent durability and

	reliability.
Other	Steam turbines are typically designed to deliver relatively large amounts of thermal energy with electricity generated as a by-product of heat generation. Overall CHP efficiencies can reach or exceed 80%.

From Table 11-11, it is noted that the desirable characteristics of an appropriate cogeneration turbine is an extraction turbine, good part load characteristics and capable of realizing up to 80% overall plant thermal efficiency.

11.9.4.6. Selected Steam Turbo-generator

The specifications of proposed turbine are summarized in Table 11-12.

Table 11-12: Turbine specifications

Type	SST-200, Single-casing, geared
Application	Industrial use
Model	Multivalve Multistage (MVMS)
Turbine design	Extraction-backpressure
Generator type	Synchronous
Power output	Up to 10 MW
Inlet pressure	Up to 110bar
Inlet Temperature	Up to 520°C
Exhaust pressure(condensing)	Up to 0.25 bar
Exhaust area	0.17 – 0.34m ²

From Table 11-12, it is noted that a multistage turbine is proposed for the powerplant cogeneration project with design capacity of 10 MW.

11.9.5.Limitations of the Design

i.) Operation at part loads

Diesel Engine power plants are not reliable base load power sources, i.e., they cannot give consistent power ratings due to load variations and the big depreciation factor. However, these Engines are highly reliable sources of standby power. This therefore means that the boiler efficiency is compromised at part loads and thus the whole system is brought low. This also means that this is an in dispatchable power source, i.e., it cannot meet all fluctuating needs of power. To this effect governing in steam turbines is introduced to help maintain the rotational speeds at constant even at part loads[101, 910, 911].

ii.) Thermodynamic limitations

In this design, thermal fluctuations are at par neglected with the assumption that thermodynamic quantities such as pressure and energy are functions of thermodynamic variables such as temperature and density, this negligence is hereby justified to an allowable extend[81]. Therefore, it has been identified that there is large potential of energy savings from diesel engine power plants and to this effect Kipevu I can be able to recover about 5.2MW of power from the flue gases according to our design analysis. The recovering and utilization of the waste gases helps to improve performance and enhance low emissions of the Engines. The waste heat recovery from exhaust gases and its conversion into mechanical shaft power then to electrical energy through a turbogenerator is highly achievable with the thermodynamic Rankine cycle.

11.9.6.Overall Design Configuration

The overall design configuration is shown in Figure 11-18.

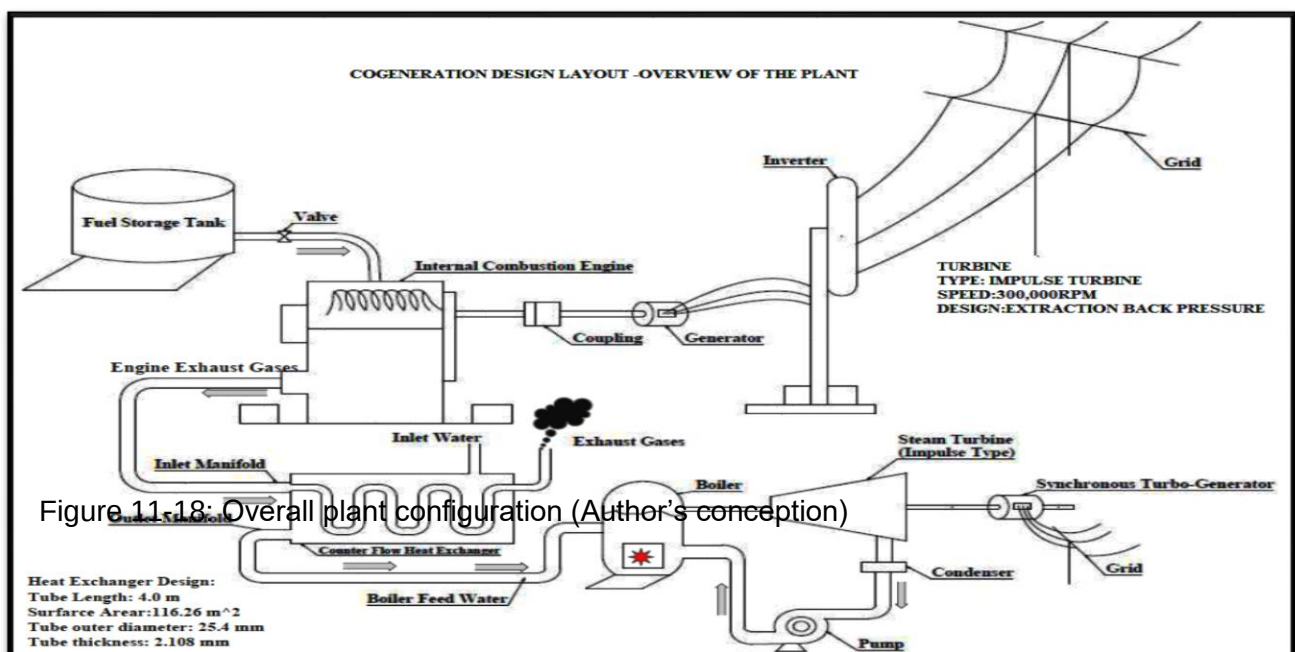


Figure 11-18: Overall plant configuration (Author's conception)

Figure 11-18 shows the overall model of the modified powerplant which includes the proposed cogeneration plant. The main elements of the overall diesel powerplant with cogeneration plant are the engines, generators for engine, generator for the turbine, exhaust gas boiler, fuel storage tanks, boiler feed water pumps, and the steam turbine.

Various design criteria are proposed for the design of the major element of the proposed cogeneration/dual cycle powerplant. These elements are the heat exchangers, exhaust gas boiler, steam turbine, the turbogenerator as well as several accessories for the plant[870, 871, 905]. This is summarized in table 11.13 below.

Table 11-13: Model cogeneration plant layout [871]

Cogeneration System Components	Specifications	Estimated Amount (KES)
1.Heat Exchanger	• Counter flow • 280 tubes ,2-tube pass, t=0.083in, di=0.834in • Tube length=4.0m, square pitch layout • Maximum Design velocity=0.820648m/s • Baffle spacing=533.4mm • Shell thickness=5.0mm • Pressure drop=2.109kPa • Mass flow rate =2.83kg/s • Exchanger area=89 sq. m	1.2M
2.Exhaust Gas Boiler	• Boiler cylinder volume = 792L • Thickness=0.423cm • Pipe grade SCH 40 • Pipe Size NPSI ¼ • Steam pressure =40bar • Steam velocity =120.213m/s • Provision for; Economizer, Superheater,	2.5M

Preheater, and feed pump

3. Steam Turbine	• Rotor Speed =30,000 rpm • Rotor type = Pelton, single casing geared • Steam pressure = 40 bar • Model = multistage multi valve • Design = extraction back pressure	12M
4. Generator	• Power output= up to 10MW • Type-Synchronous	.0.8m
5. Other interconnections	• Feed hose, bolts, nuts, pressure gauges, valves etc.	0.6m

Total cost=ksh.20m

Cost of unit of power at KES.7.00 per kwh

Payback period=1year

From Table 11-13, it can be noted that the main elements of the proposed design are the heat exchanger, turbogenerator, steam turbine and exhaust gas boiler. Each has unique important parameters like power output, type of turbine and exhaust pressure for the generator. Important parameters for the steam turbine are rotor speed, inlet pressure, and rotor type.

11.9.7. Conclusion

It has been identified that there is huge potential of energy savings using waste heat recovery technologies. Waste heat recovery defines capturing and reusing the waste heat from internal combustion engine for heating, generating mechanical or electrical work and refrigeration system. Waste engine heat can be recovered from the cooling and exhaust systems using the Rankine or organic Rankine cycles and used to generate extra power as well as process heat.

If these technologies were adopted by the diesel powerplants, then it will be result in efficient engine performance and Low emission. The waste heat recovery from exhaust gas and conversion into mechanical power is possible with the help of the Rankine cycles. Kipevu I diesel power plant has the potential to generate about site for recovery and utilization of this waste heat with a possible capacity of 5.2MW of power. The p5.2 MW extra power from the exhaust heat recovery system with a Rankine cycle turbine plant in addition to the existing 60 MW diesel engine plants. The cogeneration system requires the design, sizing, and careful selection of the heat regenerators. The exhaust gas boiler, the steam turbine, and the turbogenerator.

11.9.8.Recommendations

Diesel power plants to adopt cogeneration as a method of boosting capacity for the stations and reducing environmental impact from diesel power plants. Since CHP is well justified to save energy and emissions as well as to utilize energy in an effective and sustainable way, we recommend that, thermal power plants in Kenya to adopt cogeneration.

Suggestions for further research work

- i.) This study recommends further research on modification of Kipevu 1 Engines to make them dual fuel i.e., to use Gaseous fuels and industrial diesel.
- ii.) Another study is recommended to study the feasibility of an organic Rankine powerplant for Kipevu 1 60 MW diesel engine plant.

CHAPTER 12

CARBON CAPTURE AND SEQUESTRATION

12. Overview

This section is published by the author in [283] carbon capture and sequestration. The study showed that with abundant and cheap fossil fuel sources of energy, the world will take long to abandon their use, hence the need for emission reducing strategies like Carbon capture and sequestration (CCS) which is viable mitigation strategy for reducing greenhouse gas (GHG) emissions in fossil-fuel power plants. Although CCS technology can mitigate the anthropogenic GHG emissions, the technologies are associated with additional water requirements for chemical and physical processes to capture and separate CO₂ and other environmental impacts like introduction of parasitic loads imposed by carbon capture on power plants hence reduced efficiency and more cooling requirements and groundwater contamination due to CO₂ leakage during geologic sequestration. The energy transition requires the decarbonizing of the power, transport, and industry sectors. Carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies will play a major role in this energy transition by cutting down emissions from new fossil fuel power plants. Main challenges facing the CCS and CCU include low oil price to make CO₂-enhanced oil recovery profitable, lack of financial incentives for CO₂ geological storage, limited acceptance, lack facilitating government policy and CCS regulations, and high capital investment.

12.1. Introduction

Greenhouse gas emission (GHG) from anthropogenic activities are the most important environmental issues of the twenty-first century. This has made the CCS (carbon capture and storage) and carbon capture and use (CCU) important technologies and approaches particularly in power generation and industrial operations to cut down emissions released to the atmosphere. CCS (carbon capture and storage) is a means of reducing greenhouse gas emissions by capturing and subsequently storing CO₂, while CCU (carbon capture and utilization) is a way of recycling carbon in the captured CO₂ by converting it into products like fuels, chemicals, or other products[912]. The climate change resulting from anthropogenic emissions of greenhouse gases (GHGs) is one of the most significant long term environmental challenges today. The greenhouse gas emissions (GHG) from the electricity sector have been growing to ever increasing electricity demands and while fossil

fuels remain the dominant source for electricity generation. There are various mitigation strategies developed aimed at reducing CO₂ emissions with technological alternatives for to reduce emissions from power plants to the atmosphere being.

- i.) Switching to less carbon-intensive fuels, e.g., natural gas instead of coal.
- ii.) Increasing the use of renewable energy sources or low carbon nuclear energy, which emit less or no net CO₂; and
- iii.) Capturing and sequestering carbon emissions.

The main challenge is that the current global demand for chemicals has no capacity to sequester enough CO₂ emissions to contribute significantly to meeting CO₂ reduction targets. The annual production of urea and methanol, the two most commercially important chemicals, can consume just 0.5% of the current 34.5 Gt/yr of the anthropogenic CO₂ emitted globally. The use of CO₂ for fuel production only delays its emissions instead of removing it over long timescales for mitigating climate change., while ‘storage’ in some chemicals is short-lived in some chemicals based on , n their use[620].

We also have other sustainability issues that should be considered before large-scale deployment of either CCS or CCU, particularly the environmental impacts to ensure that ensure that climate change mitigation is not done at the expense of other environmental factors. Impacts should be assessed on a life cycle basis, to avoid shifting the environmental burdens from one life cycle stage to another [620, 758].

12.2. Carbon Dioxide Removal (CDR) and Greenhouse Gas Removal (GGR)

All emission pathways seek to limit global warming to 1.5 °C or 2 °C by the year 2100 assume the use of CDR approaches in combination with emission reduction. There are two main strategies for removing carbon directly from the atmosphere i.e., by planting and forest restoration, which is referred to as conservation efforts, and by direct air capture (DAC). Carbon dioxide removal (CDR) which is also known as negative CO₂ emissions, involves the removal of carbon dioxide gas (CO₂) from the atmosphere and storing in geological, terrestrial, or ocean reservoirs, or in products.

12.2.1. Carbon Dioxide Removal (CDR)

CDR methods are applied to remove CO₂ from the atmosphere, some of which are explored below. CDR is also known as Greenhouse Gas Removal (GGR) when used to refer to greenhouse gases in general, although the focus is quite often atmospheric removal and subsequent storage of CO₂. Carbon dioxide removal (CDR) refers to anthropogenic activities

that remove CO₂ from the atmosphere and store it in geological, terrestrial, or ocean reservoirs, or in products. They include existing and potential anthropogenic enhancement of biological or geochemical sinks as well as direct capture from air and storage. This however does not include natural CO₂ uptake not directly caused by human activities. Similar definitions are commonly used for "net negative greenhouse gas emissions", "net zero CO₂ emissions" and "net zero greenhouse gas emissions". Geoengineering or climate engineering is used for both CDR or SRM (solar radiation management, if used at a global scale, but they are no longer used in IPCC reports addresses the root cause of climate change and is a major strategy in reducing net emissions and managing risks related to high CO₂ levels in the atmosphere. In CDR, CO₂ is removed from the atmosphere and locked away for decades or centuries in plants, soils, oceans, rocks, saline aquifers, depleted oil wells, or long-lived products like cement[99].

Greenhouse gas removal (GGR) or negative greenhouse gas emissions refers to the removal of greenhouse gases (GHGs) from the atmosphere through human activities, which is in addition to what occurs via natural carbon cycle or atmospheric chemistry processes. Within the context of net zero greenhouse gas emissions targets, carbon dioxide removal (CDR) is increasingly integrated into climate policy new element of mitigation strategies. Both CDR and GGR methods are referred to as negative emissions technologies (NET), and may be cheaper than preventing some agricultural greenhouse gas emissions[39, 620].

Carbon dioxide removal (CDR) methods includes carbon sequestration methods like afforestation, carbon farming (agricultural practices that sequester carbon in soils), enhanced weathering, etc. and direct air capture combined with storage. A comprehensive life cycle analysis of the process must be performed. to assess whether net negative emissions are achieved by a particular process.

It was concluded by the 2019 consensus report by the US National Academies of Sciences, Engineering, and Medicine (NASEM) that applying existing CDR methods at scales that can be safely and economically deployed, can remove and sequester up to 10 gigatons of carbon dioxide per year which can offset . greenhouse gas emissions at about a fifth of the rate at which they are being generated.

12.2.1.1. Direct Air Capture

Direct air capture (DAC) applies chemical or physical processes to extract carbon dioxide from the atmospheric air. If the CO₂ is then sequestered in safe long-term storage it is

called direct air carbon capture and sequestration (DACCS). The process achieves a "negative emissions technology" (NET). As of the year 2022, DAC is loss making process since the cost of using DAC to sequester carbon dioxide is far much more than the carbon price[913]. Figure 12-1, shows the growth in direct air capture operating capacity from 2010 to 2021.

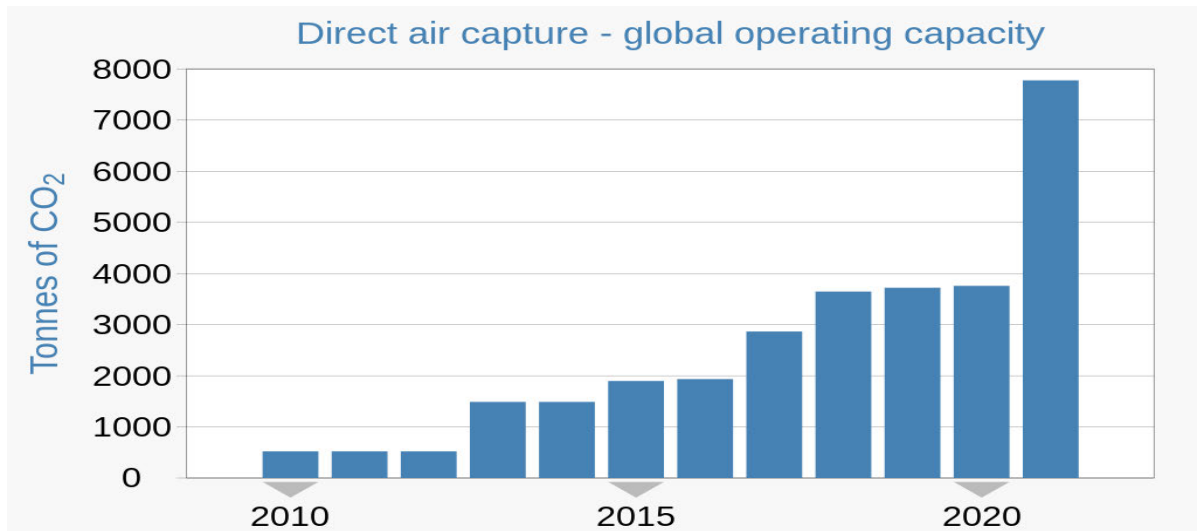


Figure 12-1: Potential for climate change mitigation.

From Figure 12-1, it is noted that the global direct air carbon capture capacity improved from about 500 tons of CO₂ in 2010 to over 7,500 tons. Of CO₂ per year in 2021

12.2.1.2. CDR Technics and Measures

Carbon dioxide removal (CDR) methods are referred to as negative emissions technologies (NETs), although not all NETs effect CPROF. Greenhouse gas removal (GGR) is used as a synonym for NETs, that encompass the removal of all GHGs present in the atmosphere[914]. By using CDR in parallel with greenhouse gas emissions reduction measures, like deployment of renewable energy, makes it less expensive and disruptive than using other efforts alone. Studies show that CDR techniques other than ocean fertilization can remove up to 10 gigatons of CO₂ per year if deployed fully globally which is about 20% of the 50 gigatons of CO₂ emitted per year by human activities. All mitigation pathways analyzed in 2018 that aimed at achieving 1.5 °C of warming involved CDR measures.

Higher rates of mitigation by CDR are also proposed but require hundreds of millions of hectares of land for biofuel crops. Research into direct air capture, geologic sequestration of carbon dioxide, and carbon mineralization can yield technological advancements necessary for higher rates of CPROF. Reliance on large-scale deployment of CDR is generally risky to

achieving target of less than 1.5 °C of warming, due to uncertainties over quick largescale deployment. Therefore strategies that rely less on CDR and more on sustainable use of energy are less risky.

The CDR methods in order of their technology readiness level. Include:

- i.) Afforestation/ reforestation
- ii.) Carbon sequestration in grasslands and croplands
- iii.) Restoration of Peatland and coastal wetland
- iv.) Improved forest management and Agroforestry
- v.) Application or use of biochar
- vi.) Bioenergy with carbon capture, direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS)
- vii.) Enhanced weathering (EW)
- viii.) Restoration of vegetation in coastal ecosystems 'Blue carbon management' in coastal wetlands which is an ocean-based biological CDR method which consisting of mangroves, salt marshes and seagrass beds.
- ix.) Fertilisation of the ocean and enhancing alkalinity of the ocean

The CDR methods having the greatest potential to limit climate are the land-based biological CDR methods i.e. afforestation/reforestation (A/R)) and/or bioenergy with carbon capture and storage (BECCS). Some proposed pathways include direct air capture and storage (DACCS). Land based agricultural CDR methods reduce emissions from sector called "agriculture, forestry and other land use" (AFOLU).

Through halting loss and degradation of natural systems and promoting their restoration can contribute over one-third of the total climate change mitigation strategies by 2030. Forests are important because trees keep the air clean, help regulate the local climate and supply habitat for numerous species. Carbon dioxide is converted by trees and plants into oxygen, using photosynthesis. Plants remove and store carbon from the air hence without them, the atmosphere would heat up quickly and destabilize the climate. Figure 12-2 shows geologic and biologic sequestration processes.

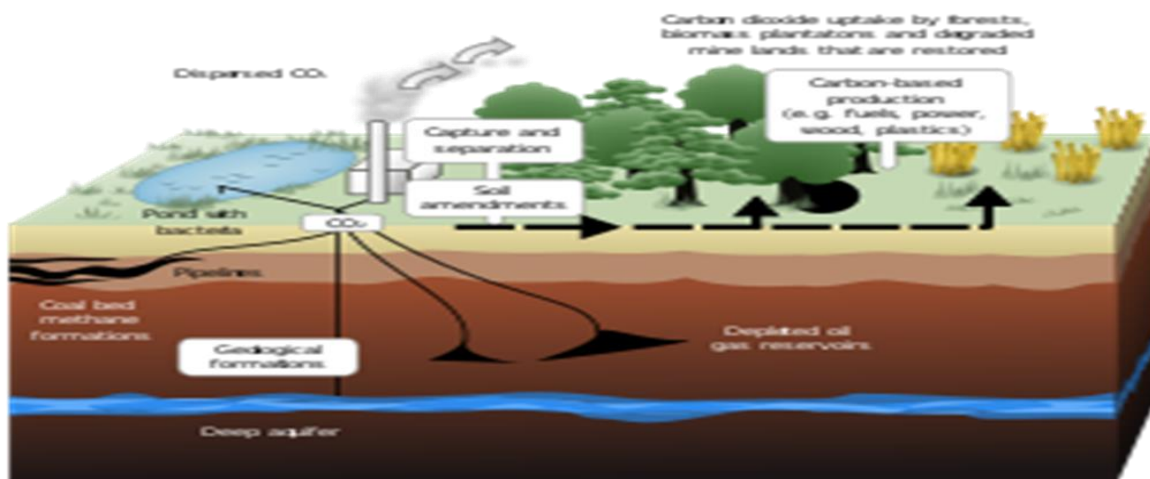


Figure 12-2: Geologic and biologic carbon sequestration of the excess carbon dioxide

From Figure 12-2, Carbon sequestration (or carbon storage) involves storing carbon, particular atmospheric carbon dioxide in a carbon pool in a process that acts like carbon sink. Carbon sequestration is naturally occurring but can be enhanced or achieved with technology, like carbon capture and storage projects. Carbon sequestration can be classified into geologic and biologic/ bio sequestration).

Carbon dioxide (CO_2) is naturally captured through biological, chemical, and physical processes which can be accelerated by changes in land use and agricultural practices like growing fast maturing plants. Artificial processes have also been developed large-scale, artificial capture and sequestration of industrially produced CO_2 and storage in subsurface saline aquifers or aging oil fields. Other technologies applied are bio-energy with carbon capture and storage, biochar, enhanced weathering, direct air carbon capture and sequestration (DACCS).

12.2.2. Removal of Methane and other Non- CO_2 GHGs

The natural elimination of non- CO_2 GHGs and organic compounds is largely initiated by the by reaction with the sunlight generated hydroxyl (OH) radicals and chlorine atoms (Cl and through heterogenous) reactions occurring on mineral dust aerosols. Several technologies for methane (CH_4) removal include enhancing the natural hydroxyl and chlorine sinks and through use of photocatalysis. The products of non- CO_2 GHGs degradation are very low concentrations and can be left in the atmosphere without additional risks, although technologies are available for implementation at a climate related scale. N_2O for having a tropospheric concentration of ~ 335 ppb, is transformed into nitrogen and oxygen, which are

main constituents of air, while the oxidation of the whole atmospheric CH₄ inventory to CO₂ can increase the CO₂ concentration by less than 0.5%, while reducing the radiative forcing substantially. No issues of storage, sequestration, and monitoring for possible leakage would therefore arise with the large-scale implementation of these NETs.[914]

However, based on the future prices of CO₂e removals, ideally based on the 20 year global warming potential to reflect the 10 year lifetime of atmospheric CH₄, further development in technology may lead to more cost competitive CO₂e removal options with CDR[914].

12.2.3. Carbon Sequestration in Oceans

Technologies that can be used to enhance carbon sequestration by oceans include artificial upwelling, Seaweed farming, ocean fertilization, basalt storage, mineralization and deep sea sediments, and adding of bases to neutralize acids but not is being practiced at largescale[914].

12.2.4. Agricultural Practices

Carbon farming is an important component of agriculture. Carbon refers to agricultural methods used to sequester atmospheric carbon into the soil and in crop parts. Carbon farming increases the rate at which carbon is sequestered into soil and plant material to create a net loss of carbon from the atmosphere. More carbon in soil improves soil water retention capacity and reduces fertilizer needs. Carbon farming can be done by individual landowners provided with incentives to invest in carbon sequestration. Carbon farming can be mixed with land management techniques like planting/restoring forests, biochar burying and restoring wetlands like peatlands and marshes[914].

12.2.5. Biochar

Biochar is charcoal formed by pyrolysis of biomass, and is an established method of carbon sequestration. Pyrolysis is high temperature heating and degradation of biomass in a low oxygen environment leading to formation of a material known as char, which is like charcoal but made by a sustainable process from biomass. Estimates by UK Biochar Research Center showed that at conservative level, biochar can store 1 gigaton of carbon per year but with great marketing effort and acceptance biochar can store 5–9 gigatons of carbon dioxide in the soil.

12.2.6.Magnesium Silicate/Oxide in Cement

The replacement carbonate in cement facilitates potential absorption of carbon dioxide over the lifecycle of concrete although the lifecycle quantities are not yet fully established.

12.2.7.Economic Aspects

CDR costs substantially differ based on the maturity of the technology employed and economics of voluntary carbon removal markets and the physical output. As an example, biomass pyrolysis generates biochar which has several commercial applications like soil regeneration and wastewater treatment. DAC cost between \$250 and \$600 per ton, compared to \$100 for biochar and below \$50 for nature-based solutions like reforestation and afforestation in the year 2021. Biochar is more carbon since it is a more durable sink with the ability to sequester carbon for hundreds or even thousands of years compared to more volatile nature-based solutions[914].

Forests can be used to create carbon credits and geospatial analytical systems can be used determine carbon offsets by conserving a forest area or a reforestation initiative. Individuals and institution can purchase carbon credits using verified retailers like ACT4. In 2021, businessman Elon Musk announced he was donating \$100m for a prize for best carbon capture technology. Some of the “negative-emission technologies” are already in large scale application with Congress passing the 45Q tax, that gives \$50 credit per ton of carbon dioxide fixed and stored hence the need for technologies that would cost less than \$50. to fix a ton of carbon dioxide[914].

12.2.8.Capture from Power Generation

Large fossil-fueled power plants account for almost half of the total CO₂ emissions from the fossil fuel combustion. These large power plants are those that emit >0.1 Mt-CO₂/year and are essential point of application for CSS and CCU emissions[915]. The thermal efficiency of this type of plant is limited to ~46%–48% by the achievable temperature of the working fluid (steam) which in turn is limited by the availability and cost of suitable materials needed to withstand the high temperatures and pressures, with current technology limiting steam temperatures and pressures to ~625°C and 250 bar, although by 2025, technological progress will raise this to 700°C and 350 bar by 2025[93, 279, 915]. Figure 12-3 demonstrates the flow of oil, air, ash, flue gases and water into out of fossil fuel power plants.

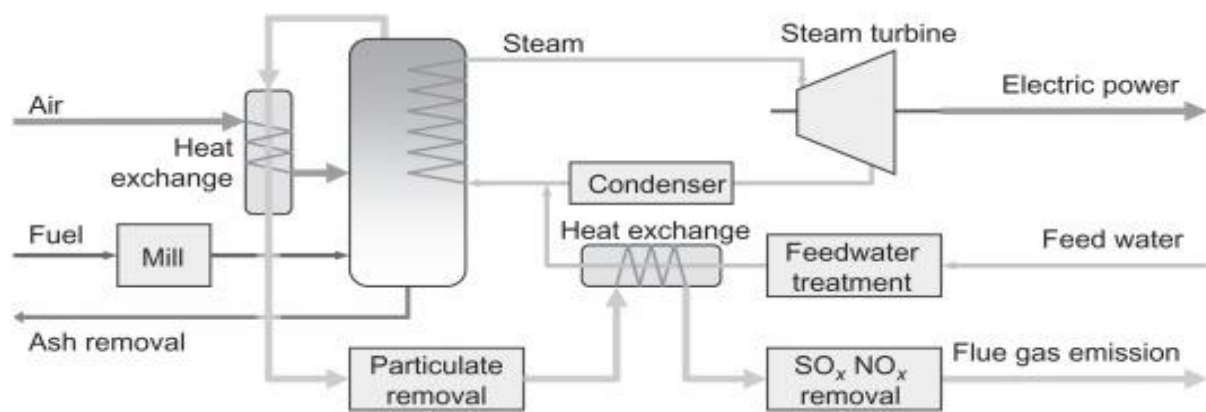


Figure 12-3: Schematic fossil-fueled electric-generation plant with points of carbon capture in power plants

The generation efficiency is better for technologies like the combined cycle power plant, in which flue gases are used to drive a gas turbine while exhausts are used to produce steam in a heat-recovery steam generator for extra power generation through a steam turbine and can achieve a thermal efficiency of 60% and even >80% if low-temperature waste heat is also recovered in a combined heat and power (CHP) application. With such efficiency, the impact per unit power generation is reduced[45, 115].

11.5.14.Flue gas Properties

Flue gas from power plants has various components in addition to carbon dioxide. They include CO, Sox, particulates, N₂, and O₂. The typical characteristics of flue gas from fossil fuel combustion are presented in Table 12-1.

Table 12-1:Typical fossil fuel combustion flue gas characteristics.[915]

Parameter	Typical range of values
Pressure	At or slightly above atmospheric pressure
Temperature	30–80°C or higher, depending on the degree of heat recovery
CO ₂	Coal-fired, 14%
	Natural gas-fired, 4%
O ₂	Coal-fired, 5%
	Natural gas-fired, 15%

N ₂	~81%
SO _x	Coal-fired, 500–5000 ppm
	Natural gas-fired, <1 ppm
NO _x	Coal-fired, 100–1000 ppm
	Natural gas-fired, 100–500 ppm
Particulates	Coal-fired, 1000–10,000 mg/m ³
	Natural gas-fired, 10 mg/m ³

From Table 12-1, it is noted that CO₂ content ranges from 3% to 15%, with gas fired plants having typically (3%–5%) at the lower end. Coal fired plants have the higher range of (12%–15%). Application of CO₂ capture from power generation can reduce these values.

Post combustion CO₂ capture is the capture from flue gases. This involves techniques that have been developed and implemented in the natural gas processing industry applicable to existing power plants. Post combustion technologies include use chemical and physical sorbents and membranes, and hybrid approaches like combining membranes with solvent or cryogenic methods[912]. Figure 12-4 shows the various approaches used to capture CO₂ in power plants.

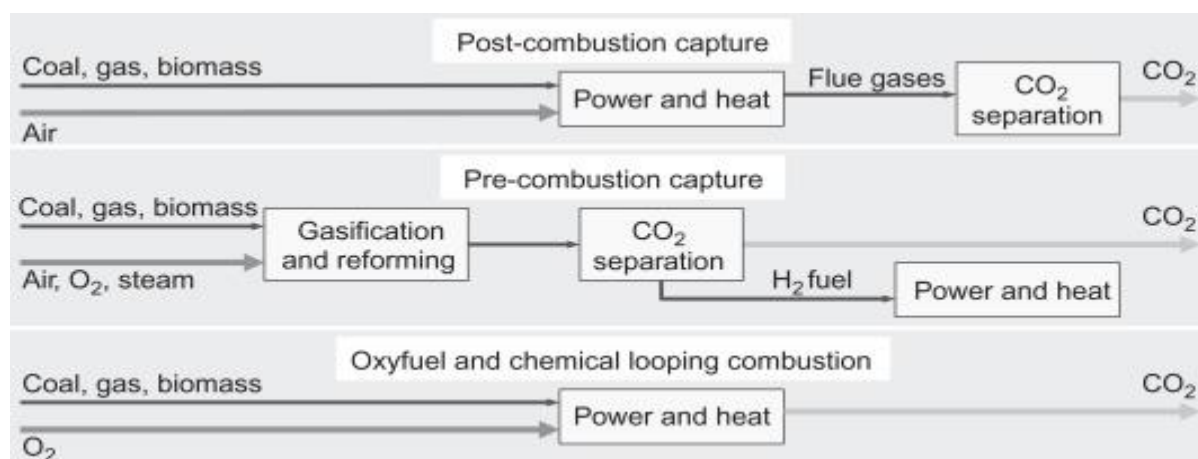


Figure 12-4: Approaches to CO₂ capture from power generation plants.

From Figure 12-4, it is noted that here are two alternatives to post-combustion capture whose aim is to modify the combustion process to produce pure or high-concentration CO₂ stream is generated. These include.

- i.) The first option involves combustion of the fuel using pure oxygen instead of air leading to a near-pure CO₂ combustion gas stream which requires minimal further processing before being compressed for transportation and storage. Combustion Oxygen may be delivered either as a gas (oxyfueling) or as an oxide called chemical looping combustion [915].
- ii.) In the second pre-combustion capture option, the fuel is partially oxidized and reacted with steam to form a CO₂ and H₂ mixture consisting of 15%–60% CO₂, from which the CO₂ can be separated by methods for post-combustion capture. These produces a hydrogen fuel stream for combustion in a conventional boiler or gas turbine, or put to other fuel uses. [912, 915].

The theoretical minimum energy needed to separate CO₂ from flue gases or syngas stream is a function of CO₂ concentration in the gas stream,. Separation of CO₂ from natural gas combustion flue gases has theoretical minimum because of low [CO₂] while post-combustion capture has higher energy requirements for different coal-fired options[915]. The relationship between separation work and CO₂ concentration is demonstrated in Figure 12-5.

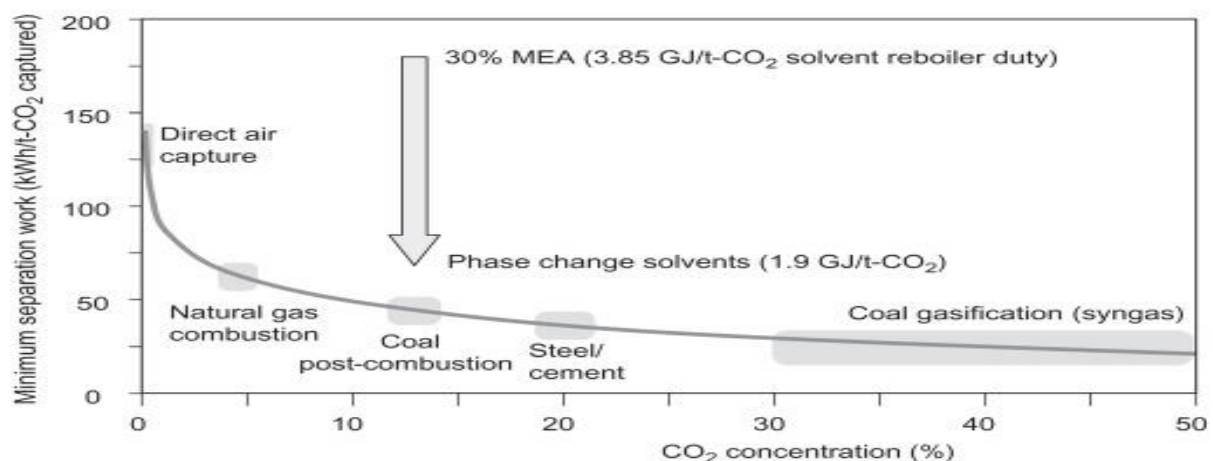


Figure 12-5: Minimum work required for CO₂ separation.

From Figure 12-5, it is noted that coal gasification (syngas) has the lowest minimum separation work compared to direct air capture and natural gas combustion. The figure also demonstrates the impact of technological progress in reducing the energy cost in the case of coal-fired post-combustion capture, from the benchmark amine capture process to the emerging phase change solvents[915].

12.2.9.CCS and CCU Technologies

Carbon capture and sequestration (CCS) and (CCU) seek to capture CO₂ from point of sources like power plants and industrial processes, to avoid release into the atmosphere. In CCS, the captured CO₂ is moved to suitable site for long-term storage, while for CCU, captured CO₂ is changed to commercial products. The different methods for carbon capture and sequestration and CCU are shown in Figure 12-6.

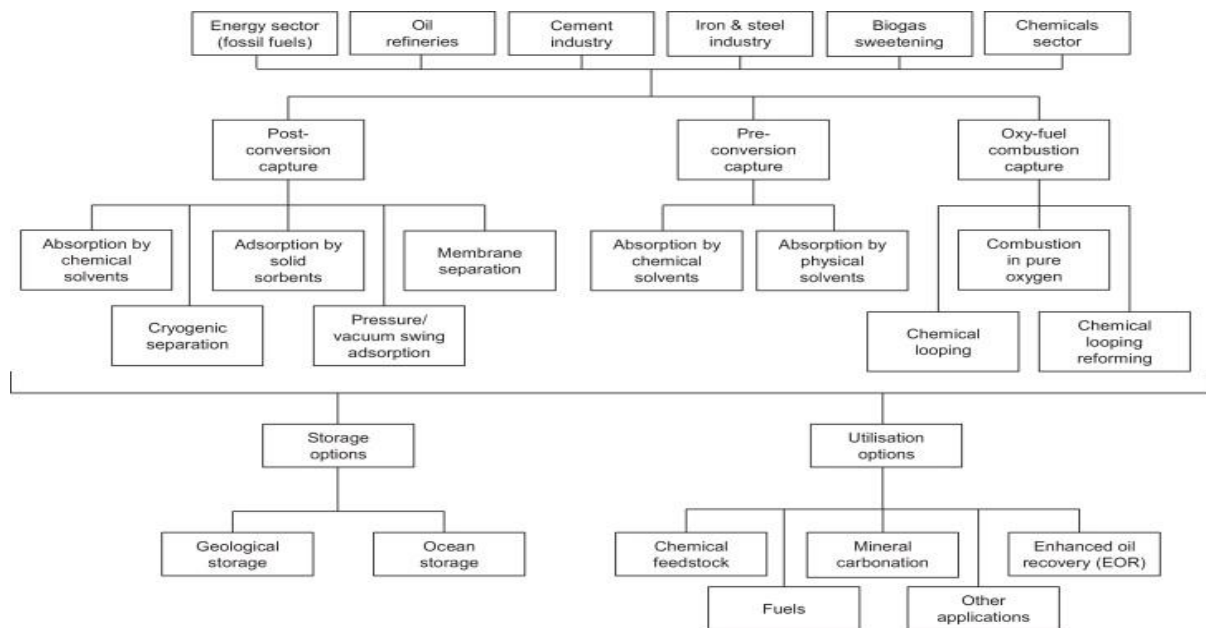


Figure 12-6: Different carbon capture, storage, and utilization option

Figure 12-6 shows the various technologies for CCS and CCU. The main storage options are geological storage and ocean storage. The various utilization options are chemical feedstock, mineral carbonation, enhanced recovery, use in fuels and other applications.

12.2.9.1. Lifecycle Assessment of CCU and CCA

Life cycle assessment (LCA) studies of different CCS options indicate that GWP from power plants can be reduced by 63–82% per unit of electricity produced based on the CO₂ capture option applied. The average GWP for pulverized coal (PC) power plants that are not equipped with CCS is 876 kg CO₂ eq./MWh while for the post-conversion capture via MEA the average value is 203 kg CO₂ eq. while oxy-fuel combustion it is 154 kg CO₂ eq. The equivalent average values for CCS at CCGT power plants is about 120 kg CO₂ eq./MWh for oxy-combustion and 173 kg for post-combustion, and 471 kg CO₂ eq./MWh without CCS. The GWP for pre-combustion capture and oxy-fuel combustion in IGCC plants is 190 and 200 kg CO₂ eq./MWh, but without CCS is 1009 kg CO₂ eq./MWh. These demonstrates a

GWP reductions of up to 82% using oxy-fuel combustion in PC and IGCC plants while the lowest by post-combustion capture in CCGT plants (63%)[912].

The results for the other environmental impacts vary but large majority show a higher impact for the plants with CCS than without CCS because of an additional coal mining and shipping required to compensate for the energy efficiency losses from the use of CCS, MEA production and ammonia emissions during absorption of CO₂ in MEA. This implies that impacts are transferred from power plants, further up or downstream from the power plants[16, 64].

The CO₂ utilization option in CCU systems influences the CO₂ savings e.g., mineral carbonation to produce MgCO₃ reduces the GWP by 4% to 48% compared to no CCU. Estimated GWP varied from 524 kg CO₂ eq. per ton of CO₂ removed for the carbonation of CO₂ directly from a power plant to 1073 kg eq./t removed when CO₂ is first absorbed in MEA then recovered for use in the carbonation process. Studies also indicated that using CO₂ recovered after the capture in MEA for production of DMC in the urea-based process can reduce GWP by 4.3 times compared to the conventional synthesis of DMC from phosgene (3 vs 132 kg CO₂ eq./kg DMC). By utilizing CO₂ from power plants for EOR, GWP can be reduced significantly (on average, by 2.3 times) compared to discharging CO₂ to the atmosphere. The CCU via microalgae capture to produce biodiesel, leads to the average GWP estimated at 209 kg CO₂ eq./MJ, which is 2.5 times higher than for conventional fossil diesel[296].

The results for the other environmental impacts of CCU differs based on the utilization options e.g. production of DMC from CO₂ reduces eutrophication by 3.6 times, acidification and photochemical oxidants by four times and ozone layer depletion by 13 times when compared to the conventional phosgene-based processes because of lower energy requirements for DMC than phosgene -based process by four times. EOR, acidification is three times higher than without utilization because of the ammonia emissions from the CO₂ capture plant. The CCU via microalgae capture for biodiesel, eutrophication is higher than for conventional diesel due to energy intensive harvesting operations. The creation of photochemical oxidants potential is both higher and lower than for conventional because of different assumptions made for aerial productivity[723, 915]..

It was established that the average GWP of all CCS options is about 276 kg CO₂ eq./t CO₂ removed, which is significantly lower than the GWP of all CCU

options considered. The average GWP of CCU via chemicals production (DMC) is about 59.4 t CO₂ eq./t CO₂ removed, which is 216 times higher than for CCS which indicates that compared to CCS, CCU is not an efficient method for removing CO₂ emissions because almost two tons of DMC need to be produced to remove one ton of CO₂. This leads to use of huge quantities of reactants, like ammonia and naphtha, that generate additional CO₂ eq. emissions. Biodiesel production has higher GWP than CCS, by four times on average, although the impact varies significantly among based on technologies and process conditions applied. For CCU via EOR and carbon mineralization, the average GWP is 1.8 and 2.9 times higher than for CCS, respectively[912, 915].

Just like the GWP, the other environmental impacts of CCU to produce DMC are significantly higher e.g., acidification is 320 times higher, ozone layer depletion and photochemical oxidants is about 2.8 times higher and eutrophication 20% higher than for CCS. CCU via biodiesel from microalgae has 9.6 times lower eutrophication and 13 times more photochemical oxidants than CCS. For EOR, only acidification is found to be 14% lower than for CCS.

12.2.10. Results and Discussion

CCS (carbon capture and storage) is a strategy for reducing greenhouse gas emissions by capturing and subsequently storing while CCU (carbon capture and utilization) involves recycling the carbon in the captured CO₂ by changing it into new products. The objective of CCS is to improve at improving the results for one environmental indicator, but CCU represents a multi-functional system. Therefore, comparing CCU with CCS or no capture should involve more than one indicator. It is also vital to establish relevant system boundaries and to define a joint functional unit, to establish a robust decision basis for application in selecting environmentally preferable option[912, 916].

The aim of CCS and CCU is to capture CO₂ emissions from point sources like power plants and industrial processes, to stop their release into the atmosphere. The destination is the main difference between CCS and CCU. In CCS, the captured CO₂ is moved to a suitable site for long-term storage[620]. The main CO₂ capture options are post- and pre-conversion capture and oxy-fuel combustion processes. The Post-conversion apply chemical absorption using monoethanolamine (MEA). It is the most mature and widely applied technique, in power plants but the use and regeneration of MEA contributes to the emissions of CO₂ and

related global warming potential (GWP), hence the development of more environmentally sustainable sorbents remain a challenge for both CCS and CCU[280, 620].

The CO₂ captured is stored in geological formations, in geological storage, which is most viable, or in the oceans, a limited by lack of knowledge on long term implications to the oceans in terms of acidity and marine species. CO₂ captured can also be used directly industrial sectors, like food and beverage, pharmaceutical industry as well as conversion into high-demand products such as urea, methanol and biofuels[113, 632].

CCS focuses on improving the results for one indicator only and CCU represents a multi-functional system. It is therefore crucial to analyze the use of more than one indicator and to establish relevant system boundaries when comparing the environmental performance of CCS and CCU systems. By applying system expansion, the compared systems provide the same functions to society with the analysis demonstrating that CCS is more beneficial over CCU if fossil electricity are part of the grid mix. However, if renewable electricity used for substitution is decided is not included in the system expansion boundaries, CCU offers the best option. Hence the choice of the modelling decision is an important issue when comparing multifunctional systems. As the society moves towards a circular economy, there will be an increased focus on the ranking of the environmental performance of use, reuse and recycling of our common goods and resources, with LCA methodology playing an important role as a tool for this purpose, and that the expansion of the system boundaries will be crucial for the correct assessment of the systems[100, 912].

Comparisons between CCS and CCU should be used as a guide only since inconsistencies in the system boundaries and functional units make it difficult to compare them on an equivalent basis. Therefore specific guidelines or ‘product category rules’ are needed for application of the LCA methodology to CCS and CCU technologies. Very important are the guidelines on the definition of the system boundaries and functional units should be established for different systems[912, 917].

12.2.11. Conclusions

Both CCS and CCU technologies seek to mitigate climate change, but are regarded as temporary solutions, especially options which merely delay the emissions of CO₂ instead of eliminating them permanently. The CCU appears a better option than CCS since CCU is unprofitable activity, but the cost-effectiveness and the environmental impacts of CCU need to be carefully evaluated on a life cycle basis to ensure a positive economic

and environmental balance. The global demand of chemicals and other products cannot provide enough capacity to capture CO₂ emissions to contribute to effectively contribute to the carbon reduction targets. Another significant challenge with CCU is that the ‘storage’ time of CO₂ which is limited by short lifespans of the chemicals and fuels produced. Therefore, there’s a need to focus research on the development of materials and products having longer lifetimes to facilitate long term storage of CO₂. Although CCS overcomes this challenge through long-term storage, CO₂ leakage is a prevailing risk that can potentially cause more damage. Also significant is the fact that deployment of large-scale CCS may come too late to reverse the impacts of climate change. Nevertheless, if the above concerns can be addressed, both CCS and CCU could play a role in mitigating climate change, together with other options such as energy demand reduction, renewables, and other low-carbon technologies.

The Life cycle assessment studies established that CCS could reduce the global warming potential (GWP) from power plants by 63–82%, with greatest reduction in oxy-fuel combustion in pulverized coal and integrated gasification combined cycle (IGCC) plants. The lowest reduction is achieved by post-combustion capture in combined cycle gas turbine (CCGT) plants. Environmental impacts like acidification and human toxicity for CCS, while for CCU, the GWP varies widely based on utilization option. Mineral carbonation may reduce the GWP by 4–48% compared to the no CCU. By using CO₂ for production of chemicals, like dimethylcarbonate (DMC), the GWP can be reduced by 4.3 times and ozone layer depletion by 13 times when compared to conventional DMC process. The Enhanced oil recovery yields GWP 2.3 times lower compared to discharging CO₂ to the atmosphere but leads to higher acidification by three times. Capturing CO₂ by microalgae to produce biodiesel leads to 2.5 times higher GWP compared with fossil diesel, while other environmental impacts are significantly higher. On average basis, the GWP of CCS is significantly lower compared to CCU options, but has other environmental impacts being higher compared to CCU except for DMC production which is the worst CCU option overall.

12.3. Performance Analysis and Design of Dual Cycle for 30 MW Gas Turbine plant

12.3.1. Overview

This section is a summary of contents in authors publications[101] co-authored by Prof. In this study, a performance analysis of a working 30MW open cycle gas turbine power plant was taken to get a general overview of role and performance of gas turbines in supply of grid

electricity. The historical evaluation of the gas turbine power plant technology is presented with features and application of gas turbines in electricity generation. It was found that a significant amount of energy is lost with the exhaust gases, which are released to the atmosphere. This amount of wasted energy was as high as 74.6% of the energy in the gas turbine fuel, which is wasteful, polluting, and unsustainable. Analysis on possible conversion from the open cycle to combined cycle plant demonstrated that subject to practical limitations, specific fuel consumption reduces by 22% and power output increases by 11.69 MW, which is 38% increase from the Rankine cycle turbine. This will improve on specific fuel consumption, generate more revenue and contribute towards greenhouse emission mitigation through avoided use of fossil fuels for extra power generated[101]

In this study, 30 MW open cycle gas turbine at Embakasi power station owned and operated by the Kenya Electricity Generating Company Plc. was analyzed. The power plant is used for peak load and emergency supply.

12.3.2.Design and Analysis

Data for this study was collected from the power plant with written Authority from the company for research purpose. Observation, document reviews, which included machine manuals, operation and maintenance logbooks, interviews, and questionnaires, were used to collect data for the research. Figure 12-7 shows a TS diagram for a gas turbine cycle.

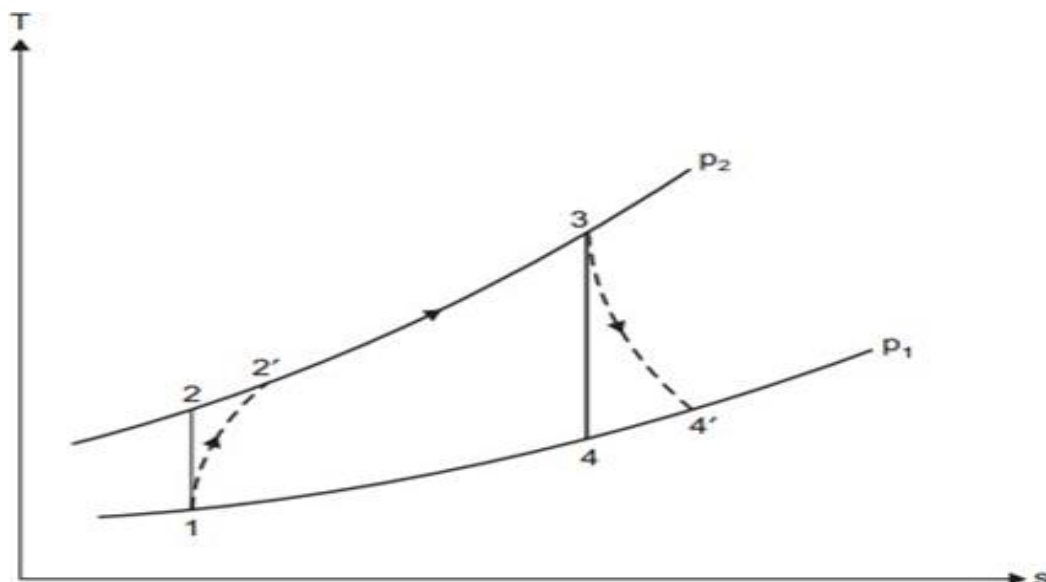


Figure 12-7: TS diagram

Figure 12-7 shows a Temperature (T) to Entropy (S) or (TS) diagram of an open cycle gas turbine plant with dotted lines showing actual paths while complete lines represent the

theoretical path. For design purpose, T4 will be 170°C which is stack temperature, which is well above the acid dew point of Sulphur in the exhaust gases thus condensation will not occur in the exhaust stack. The steam is condensed in a fan driven condenser and the water recirculated into the exhaust heat recovery steam generator [11, 12]. A horizontal HRSG with single pressure was chosen for this design.

The calculations were based on the following assumptions.

- i.) Compressor isentropic efficiency=90% ii.) Turbine isentropic efficiency=90% iii.) Combustion pressure losses, CL = 4%
- iv.) Firing temperature, $T_3 = 1100^\circ\text{C}$ (1373K)
- v.) Exhaust gas temperature, $T_4' = 551^\circ\text{C}$ (824K)
- vi.) Cp of exhaust gases =1.185kJ/kgK

For a unit mass of air:

A. Power plant Energy balance

- i.) Energy from the fuel produced by the fuel is given by:

$$Q = \dot{m} C_v$$

- ii.) Energy lost in the cooling air:

$$Q = m_a * c_a * \Delta t$$

Energy in exhaust of gas turbine:

- iv.) Unaccounted power=fuel power - (Energy lost to cooling air+ Energy lost in exhaust+ Indicated power)

Where m_e is fuel mass flow, c_p is exhaust gas specific heat at constant pressure, C_a is heating capacity of air, Δt is the temperature difference between inlet and outlet, Q is lower calorific value of the fuel, energy content of fuel.

Performance indicators for Embakasi Open Cycle Gas Turbine are shown in Table 12-2.

Table 12-2: Design parameters for Embakasi gas turbine plant (full load)

Component	Parameter	Symbol	Unit	Value
	Inlet temperature	T_1	$^\circ\text{C}$	27
	Outlet temperature	T_2	$^\circ\text{C}$	367

Compressor	Inlet pressure	P_1	bar	1
	Outlet pressure	P_2	bar	12.7
	Mass flow rate (Air)	$\dot{m}_a$	kg/s	138
Combustion chamber	Fuel consumption (flow rate)	$\dot{m}_f$	kg/s	1.5
	Inlet temperature			
	Air-fuel ratio	T_3	$^{\circ}\text{C}$	1100
Gas turbine		A: F		18.5:1
	Outlet temperature	T_4		551
	Exhaust gas flow (flow rate of gas)	$\dot{m}_{eg}$	$^{\circ}\text{C kg/s}$	141.1
Other data	GT Thermal efficiency	$\eta_{th P}$	% MW	33.3
	GT Power output			30

From Table 12-2, the design parameters are presented which shows that the gas turbine has a thermal efficiency of 33% compressor inlet and out pressures of 1bar and 12.7 bars respectively, air flow rate of 138 kg/s, and air fuel ratio of 18.5:1.

12.3.3. Performance Analysis of the Gas Turbine

The actual performance of a powerplant is determined by various performance parameters which include plant use factor, plant capacity factor, load factor, reserve factor, diversity factor and demand factors.

Table 12-3: Power plant performance factors

Factor	Equations	Value
Plant use factor	$\frac{\text{Output of power station (kWh)}}{\text{Plant capacity} * \text{hrs of plant operation}}$	0.08
Plant capacity factor	$\frac{\text{Average demand on the power station}}{\text{Installed capacity of the power station}}$	0.26

Plant operating	$\frac{\text{Duration the plant is in actual service}}{\text{Time Duration considered}}$	0.29
Load factor	$\frac{\text{Average load}}{\text{Maximum demand}}$	0.30
Reserve factor	$\frac{\text{Load factor}}{\text{Capacity factor}}$	1.15
Diversity factor	$\frac{\text{Total sum of individual maximum Dema}}{\text{Maximum demand on power station}}$	1.29
Demand factor	$\frac{\text{Maximum demand}}{\text{Connected load}}$	0.87

Table 12-3 summarizes that the turbine parameters in terms of work input of the compressor, work output of the turbine and thermal efficiency per kilogram of air and air fuel mixture.

The performance indicators for the operating gas turbine are summarized in Table 12-4.

Table 12-4: summary of existing gas turbine analysis

Parameter	Formular	Value
work in put (compressor)	$Wc = Cp(T_2' - T_1)$	357.5KW
work output (turbine)	$Wt = Cp(T_3 - T_4')$	551.745KW
net work	-	194.245KW
thermal efficiency	$\frac{\text{net work}}{\text{heat supplied}} * 100\%$	26.4%

Analysis for the turbine from Table 12-4 shows that the thermal efficiency of the powerplant is about 26.4% which shows wasted energy in the fuel to the tune of 73.6%. This is wasteful and unsustainable use of energy.

12.3.3.1. Energy Balance of the Power plant

Table 12-5: Energy balance for Embakasi gas turbine power plant

Energy	Percentage%
Energy lost in cooling air	20.00%
Energy in exhaust	27.16%
Indicated power of the gas turbine	42.50%
Unaccounted for power	10.34%

From Table 12-5, it is noted that the indicated power of the gas turbine is 42.50% with the remainder being lost to exhaust, coolant, and other losses.

12.3.3.2. Waste Heat Recovery Steam Generator (HRSG)

The average temperature of exhaust gases is 551°C. hence $m_e C_p (551-170)^\circ\text{C} = 381m_e C_p$, is recoverable heat where m_e is mass flow rate of exhaust gases. At design specifications $m_e=141.1$ kg/s and C_p for exhaust gases at 500°C=1.185kJ/kg.k.

Total heat lost = 1.185x381x141.1kg/s=68,704.53 kJ/s

12.3.3.3. Specific Fuel Consumption of Existing Steam Turbine

The specific fuel consumption refers to fuel consumption per unit power output which is computed as follows.

$$\text{turbine} = \frac{\text{mass flow of fuel}}{\text{power out put of gas turbine}} = \frac{1.5 * 3600}{30000} = 0.18 \text{ kg/kWh}$$

Specific fuel consumption of the proposed combined cycle power plant

$$= \frac{1.5 * 3600}{38940} = 0.14 \text{ kg/kWh} \text{ which implies a reduction of 22.22\%}$$

12.3.4. Results and Discussion

- i.) The actual thermal efficiency of the open cycle power plant is 29.4%, which is less than the theoretical value of 33% indicating diminishing performance and too much waste of fuel and energy in exhaust gases. This is unsustainable use of energy resources, which should be discouraged.
- ii.) The Rankine cycle steam turbine can have generated net power of about 11.69 MW which will effectively increase the power plant capacity from 30 MW to 41.69 MW, an increase of 39% increase.
- iii.) Conversion to a combined cycle plant is expected to reduce specific fuel consumption by 22.2% hence an improvement in fuel economy for power

generation.

- iv.) Conversion from open cycle to combined cycle gas turbine power plant requires significant capital investment and hence needs optimization of the design to achieve the objective of higher efficiency, least cost and environment protection.

12.3.5. Conclusion

A gas turbine is a versatile plant with wide application in industry, aviation, and stationery applications including electric power generation. An open cycle gas turbine plant is the most basic design with thermal efficiency just up to 33% and has challenges in fuel wastage, environmental pollution, and unsustainable role in long-term achievement of sustainable electricity. A performance analysis of Embakasi open cycle power plant showed poor power plant performance indicators like thermal efficiency, load factor, plant capacity and plant utilization factor and high specific fuel consumption which calls for improvement if a gas turbine must play a sustainable role in a grid power electricity mix. A proposed conversion of the 30 MW open cycle plant promises to significantly improve the performance of the gas turbine in grid electricity generation. It was shown that conversion to a CCPP would lead to total combined power output of 41.69 MW, which means an extra 11.69 MW from the bottoming cycle (steam turbine) and an overall combined efficiency of 53.5%, reduced specific fuel consumption and environmental pollution from avoided generation from more fossil fuels sources for the extra power generated. It is unsustainable to use open cycle turbines for grid electricity supply and should be discouraged and replaced with either renewable energy sources or more.

12.4. Performance Analysis of 61 MW Muhoroni Open Turbine Power Plant

This section is published in [299] co-authored by Prof. Oludolapo. This study was a performance analysis with the aim of improving the performance of an operating gas turbine at Muhoroni, Kenya. Data was collected by observation, questionnaire, interview, and document analysis and used for performance analysis and review. The analysis of the power plant performance indicators showed that plant utilization is low with low load factor and hence low generation from the power plant because of high costs of generation and hence low demand which is limited to peak power supply. The powerplant has two operating gas turbines with recoverable exhaust heat energy of 119.4 MW_{th}. The study recommends installation of a 20 MW Rankine cycle steam turbine with exhaust heat boiler for generation of steam. Recovery and applications for the hot cooling air are recommended is also

recommended[299].

12.4.1.Introduction

Gas turbines are characterized by high consumption of energy in compression, low thermal efficiency for the open cycle gas turbines and environmental emissions from the consumption of fossil fuels. Open cycle gas turbines also emit exhaust at high temperatures with significant quantities of recoverable thermal energy while the thermal efficiency of an open cycle gas turbine is low, between 20 and 30% compared to 38 to 40% for a modern steam plant, which implies wasteful use of fuel power [3, 7, 8]. The cycle or thermal efficiency of the open cycle turbines are low because of the mentioned inefficiencies hence the need to increase efficiency by use of advanced cycles like combined cycles [9]. Low thermal efficiency, high cost of fuel and environmental concerns associated with fossil fuel sources have set in motion a transition that seeks to increase energy efficiency and increased use of renewable energy sources in power generation. The main limitations of gas turbine plants lack self- starting capability, low overall thermal efficiency, they have very high rotor speeds hence challenge with balancing, high degree of irreversibility's and low part load efficiency.

12.4.2.Methodology

This study involved data collection and analysis from an operating gas turbine powerplant based at Muhoroni in Kenya. Data was collected from the site by document analysis, observation, interview, and questionnaire. Important data included the operating parameters like temperatures, flow rates, speeds and capacities of the main plant and equipment. Generation and operation logs provided data on powerplant actual technical operation and maintenance activities and status as well actual power generation, consumption, and output.

This collected information was then tabulated and/or put in graphs. These results were then used in thermodynamic formulae to obtain certain parameters key in designing of the Heat Recovery Steam Generator which consists of the Economizer, Super heater among other modules. Other key designs included steam turbine, condenser, and cooling tower. A computer aided design software was then employed in the design of the heat recovery steam generator.

Combined cycle plants employ a basic employ a basic Bryton cycle/gas turbine cycle and another thermodynamic cycle like the Rankine cycle. Heat engines are only able to utilize a small portion of the energy supplied to o useful work, normally less than 50%. In combined cycle plants, a gas turbine is coupled to a generator for electricity generation while the waste

heat in flue gases exiting the turbine is used to generate steam for operation of a steam turbine in a Rankine cycle for extra power generation thus increasing the overall thermal efficiency. For maximum efficiency, the thermal difference between the heat source and heat sink must be as high as possible. This objective is realized by using both the Brayton (gas) cycle and Rankine cycle (steam) thermodynamics cycle. The gas turbine is hence the most important component in the combined gas-steam cycle, provided that the steam cycle utilizes the exhaust heat from the gas turbine by means of a heat recovery steam generator (HRSG). In a combined cycle powerplant, generally about 60% is generated by the gas turbine and about 40% by steam turbines. The general construction of a combined cycle gas turbine is presented in Figure 12-8.

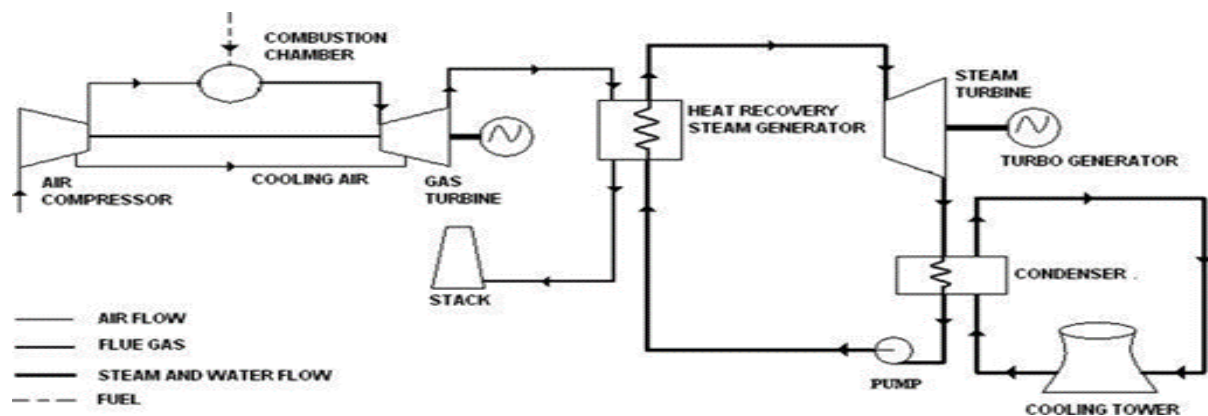


Figure 12-8: Schematic diagram of combined cycle power plant[299]

Figure 12-8 shows the various elements of the combined heat gas turbine power plant in addition to the basic elements (turbine, combustor, and compressor). They include the Heat recovery steam generator (HRSG), steam turbine, turbo generator, condenser, cooling tower, feedwater pump.

12.4.3.Design Parameters

Table 12-6: Design Parameters

Component	Parameter	Unit	Value
Compressor	Inlet Temp	°C	25
	Outlet Temp	°C	364

Combustion chamber	Inlet pressure	bar	1
	Outlet pressure	bar	12.3
	Mass flow rate (air)	Kg/s	139
	Fuel consumption (flow rate)	Kg/s	1.85
	Inlet Temp	°C	1100

Table 12-7: The Combustion Characteristics of The Gas Turbines at The Muhoroni Power Station

Device /component	Parameter	Unit	Value
Gas Turbine	Air fuel ratio	-	16:1
	Heat rate	KJ/kWh	-
	Outlet Temp	°C	572
	Exhaust gas flow	Kg/s	141
Other Data	GT thermal efficiency	%	34.01%
	GT power output	MW	30

Table 12-8: Power plant performance factors of the Muhoroni gas turbine power plant

Factors	Value
Installed capacity	61 MW
Plant Use Factor	0.08
Plant Capacity Factor	0.31
Plant Operating Factor	0.27
Load Factor	0.30
Reserve Factor	1.15
Diversity Factor	1.24

From Table 12-8 it is noted that the powerplant has a very low use factor of 0.08 mainly because it is used as a peak load powerplant hence its use is limited. The capacity factor is low at about 0.31 meaning that the powerplant capacity is not fully used and is often loaded below capacity of 61 MW hence consumers could be paying for significantly idle capacity. Effort to reduce unit cost of power will make it more attractive and will sell more to the grid earning more revenue for investors and reduce idle capacity which is paid for by consumers.

12.4.4. Results and Discussion

This study shows that several factors affect the power output of a gas turbine such as relative humidity, ambient pressure, and ambient temperature. The combined capacity of the power plant is 61MW and consists of two gas turbines with total installed capacity of 61MW. Based on exhaust gas design temperature of 1700°C, the recoverable heat energy from the two turbines operating at full load is 119.4 MWth. This recoverable heat will be subjected to heat recovery from the heat recovery steam generator, the economizer, and superheater. The recovered waste heat is then used to generate steam to run a steam turbine for extra electricity generation.

Performance analysis of the powerplant shows that it has a utilization factor of 0.08 which implies that the powerplant is idle most of the time. This is because the powerplant is mainly used for peak power supply and switched off most of the time. Since the cost of power is a function of fixed and variable costs, customers pay for idle power making it a burden to the consumers and investors.

This study demonstrated that there is huge amount of recoverable heat energy exhausted to the atmosphere. The Rankine cycle is efficient and is commonly used in waste heat recovery. The authors recommend similar studies with organic Rankine cycle in place of the ordinary Rankine cycle adopted in this study. Studies on recovery of heat from the compressor cooling air for process or low temperature power generation is also recommended. The heat from the cooling air can be used to preheat the water before being taken to the super heater. We recommend the introduction of intercoolers between the compression stages to reduce the power consumed by the compressor and generally improve the cycle efficiency. The efficiency of a gas turbine can be improved by introducing an intercooler between the compressor stages. The intercooler is used to reduce the temperature at the high-pressure compressor, causing reduced consumption power on compressor and lower output temperature at high pressure [26].

Gas turbines power plants with high pressure ratios can use an intercooler to cool the air between stages of compression, allowing you to burn more fuel and generate more power. Intercooling provides significant benefits to the Brayton cycle gas turbine power plant through decreasing the work of compression for the high-pressure compressor (HPC), which allows for higher pressure ratios, thus increasing overall efficiency. Switching cheaper and renewable fuel is another feasible area for further investigation as a strategy to minimize pollution from gas turbine power plants.

12.4.5. Conclusion

For our research to be successful, the Combined Cycle Power Plant (CCPP) needs to be functioning properly i.e., the gas turbine, steam turbine and the Heat Recovery Steam Generator (HRSG) need to be functioning optimally. Various operating parameters such as ambient temperature and compression ratios were seen to have a telling say in the efficiency of the power plant. The power plant in question (Muhoroni Power Plant) has installed capacity of 60 MW with two gas turbines of a capacity 30 and 31MW installed capacity and operates at thermal efficiency of 25.68% efficiency at full load. The current design of the gas turbines is an open cycle gas turbine which is inefficient and therefore wasteful. An exhaust heat recovery system is proposed for the recovery of waste heat in flue gases to generate steam for extra power generation by a Rankine cycle steam turbine. Total recoverable heat in exhaust gases is $119.4 \text{ MW}_{\text{Th}}$

The study showed that it is possible to increase generation by an extra 20.133 MW of electricity by installing a Rankine cycle steam turbine and increase the overall cycle efficiency by 54.2%. This will increase total installed generation capacity to 80.133MW from the current installed capacity of 61 MW. The proposed design in this research also incorporates a deaerator on the feed water loop for removal of dissolved gases from the feed water. Dissolved gases are undesirable as they bring about corrosion on heat exchanger surfaces. A bypass diffuser is also incorporated in the proposed design to provide standby a route of the exhaust gases whenever the (Heat recovery steam generator (HRSG) is out of service, hence provide a direct exhaust path to the atmosphere. Another feature is the catalytic reduction that use ammonia in presence of a catalyst to convert nitrogen oxides in the exhaust gases into harmless products of water and hydrogen hence limiting environment pollution from the plant. This will make the proposed powerplant more environmentally sustainable.

12.4.6.Recommendation

This study demonstrated that there is huge amount of recoverable heat energy exhausted to the atmosphere. The Rankine cycle is efficient and is commonly used in waste heat recovery. The authors recommend similar studies with organic. Rankine cycle in place of the ordinary Rankine cycle adopted in this study. Studies on recovery of heat from the compressor cooling air for process or low temperature power generation is also recommended. The heat from the cooling air can be used to preheat the water before being taken to the super heater. We recommend the introduction of intercoolers between the compression stages to reduce the power consumed by the compressor and generally improve cycle efficiency. The efficiency of a gas turbine can be improved by introducing an intercooler between the compressor stages. The intercooler is. used to reduce the temperature at the high-pressure compressor, causing reduced consumption power on compressor and lower output temperature at high pressure. Gas turbines power plants with high pressure ratios can use an intercooler to cool the air between stages of compression, allowing you to burn more fuel and generate more power. Intercooling provides significant benefits to the Brayton cycle gas turbine power plant through decreasing the work of compression for the high-pressure compressor (HPC), which allows for higher pressure ratios, thus increasing overall. efficiency. Switching cheaper and renewable fuel is another. feasible area for further investigation as a strategy to minimize. pollution from gas turbine powerplants

CHAPTER 13:

BIOMETHANE PRODUCTION AND APPLICATIONS

13. Overview

The content of this chapter is published as a book chapter [28] and conference paper [389] on biogas cleaning and upgrading. As the world seeks for energy sources with low carbon emissions, conversion of more polluting coal and oil uses to natural gas has demonstrated potential as a viable option in the short and middle term. However, the transition to net zero emissions may leave some stranded assets and investment. Since natural gas and biomethane have similar properties, biomethane is a viable renewable energy substitute for natural gas crating coal/oil-natural gas-biomethane transition pathway. This chapter presents the production, properties, and application of biomethane applications.

Biomethane production generally involves the cleaning to remove minor unwanted components of biogas like hydrogen sulphide (H_2S) and moisture (H_2O) and upgrading in a process that involves the removal of carbon dioxide (CO_2) to increase the concentration of CH_4 to 95–99% and reduce CO_2 concentration to 1–5%, with little or no traces of hydrogen sulphide (H_2S). Biomethane gas is a flexible and easy to store fuel having similar properties and applications as natural gas with no need to modify the settings for natural gas devices and equipment. Biomethane can be used for industrial and domestic applications ranging from thermal and power generation and feedstock for processes like the Fischer-Tropsch (FT) for fuels manufacturer and direct power generation in hydrogen or biogas fuel cells like production of green hydrogen. Therefore, biomethane promises to play a leading role in the energy transition through hydrogen, electricity, and other renewable fuels production. Biomethane production by biogas upgrading methods include the pressure swing adsorption which has an option of temperature swing adsorption, absorption technics based on amine, membrane separation, cryogenic separation, and biological separation. The technology adopted may depend on factors like costs, quality of products, location, and technology maturity and requirements.

13.1. Introduction

Biomethane or upgraded biogas is made by qualitative processing of raw biogas through several steps to remove impurities mainly carbon dioxide. Biomethane as a fuel provides new opportunities at different levels for the society. In this chapter, various methods of

biomethane production are described and compared[206, 360]. There is growing interest in the use of biomethane as a renewable substitute of natural gas in applications like transport fuel which has created demand for biogas upgrading. This chapter is a critical review that summarizes the state-of-the-art technologies used in cleaning and upgrading. Covered in the review are the description of biomethane production methodologies, scientific and technical outcomes related to them, bio-methanation efficiency, challenges, and feasibility of the technologies [164, 918].

13.2. Biomethane Production

There are many potential pathways for producing renewable natural gas or biomethane namely biomethane from biogas upgrade, natural gas by power-to-gas from renewable electricity and CO₂ and synthetic Natural Gas from gasification of biomass. Power-to-gas is a pathway that uses peaks of renewable electricity to produce Hydrogen and which is used to fix carbon dioxide through methanation reaction while synthetic natural gas is biomass gasification and syngas upgrading to synthetic natural by application of thermochemical processes [28].

Biomethane production from biogas and syngas upgrading represent effective pathways to achieve targets set by greenhouse gas emissions and global climate change. The use of biomethane in transport also can satisfy the goal to reduce the average GHG emissions from the production and use of fuels and is estimated that biomethane can count towards the target of 32% renewable energy share from EU energy consumption and towards a sub-target of minimum 14% of the energy consumed in the transport sector by 2030 [919]

Biomethane, which is also called renewable natural gas is a near-pure methane made by biogas upgrading. This is a process that removes any CO₂ and other contaminants present in biogas. Biomethane is also made by gasification of solid biomass followed then followed by methanation[920].

Biomethane is a valuable energy resource that can be produced from waste streams through anaerobic digestion which produces biogas. by action of by a consortium of microorganisms in the absence of oxygen. The quality of biogas varies due to presence of impurities lead by carbon dioxide 25%–50%, while other impurities are in smaller proportions include hydrogen sulfide, nitrogen, moisture, ammonia and hydrogen [921].

Raw biogas has undesirable contaminants like CO₂, and H₂S from the production stream which are removed by biogas upgrading process[922]. Biomethane can be made by

upgrading biogas through removal of carbon dioxide and other constituents of biogas. Biomethane can also be made by gasification of solid biomass then followed by methanation to increase methane composition to greater than 90%. Biomethane is a natural gas and with wide range of applications with potential to reduce emissions by 60-80% depending on the type of feedstock used in biogas production. [923, 924].

13.3. Upgrading Biogas

Upgrading accounts for about 90% of total biomethane produced globally by using different properties of the various constituents of raw or cleaned biogas to isolate or remove them. Water scrubbing and membrane separation jointly account for about 60% of biomethane production globally today [37]. Upgrading processes apply process techniques to remove the biogas impurities, mainly carbon dioxide[729]. Upgrading biogas is alternative avenue for carbon dioxide (CO₂)sequestration while at the same time increasing the quality and energy content of biogas for enhanced applications [925].The challenge with upgrading technologies is that they are energy intensive and can be substituted with photosynthetic microalgae process which use CO₂ in biogas to produce value-added products and energy-rich biomethane

The various technology options applied include physical and chemical absorption, adsorption, membrane, biological and cryogenic separation. Several other methods are still under research and development with a few being practiced at laboratories or small scale. Important parameters used to compare different methods final methane purity, methane losses, investment and operational cost, level of maturity among others. The upgrading methods that have reached commercial scale exploitation are the Pressure Swing Adsorption, chemical scrubbing, Water scrubbing, , Membrane separation, and Cryogenic separation[919].

13.4. Thermal Gasification of Solid Biomass Followed by Methanation.

In this process, high temperature of between 700-800°C) are used to break down solid biomass at high pressure in oxygen deficient environment. This process converts biomass into a mixture of gases, consisting of CO₂, H₂, and CH₄ often collectively called syngas. Syngas is cleaned to remove corrosive and acidic constituents. Then by use of catalysts, methanation is done by reaction between H₂ and CO or CO₂ to produce methane. Any remaining CO₂ or water is removed at the end of this process. Biomethane gas has a lower calorific value (LCV) of about 36 MJ/m³. This gas is fully compatible for use in natural gas

vehicles[322, 926]. The gas produced is indistinguishable from natural and hence can directly substitute natural gas in distribution and transmission infrastructure as well as end-user equipment applications [37].

Biomass gasification is an important technology for wider use of biomass as a source of energy. Gasification is a thermochemical conversion process done in limited supply of oxygen to produce a gaseous mixture called syngas which consists of mainly of hydrogen and carbon monoxide[310]. Carbon conversion rate is the key measure of the efficiency of gasification process. For a circulating fluidized bed gasifier, maximum carbon conversion reported is 98–99%[310]. Gasification is a mature technology used to convert carbon-rich biomass to useful combustible gas mixtures e.g. carbon monoxide, hydrogen, and methane. Conversion is achieved by reacting biomass with oxygen in air steam, and carbon dioxide at temperatures higher than ($>600\text{ }^{\circ}\text{C}$)[648]. Gasification is classified as a thermochemical conversion process carried out in a limited supply of oxygen to produce a gaseous mixture called syngas made up hydrogen and carbon monoxide. Carbon conversion is a key measure of gasification efficiency. Maximum carbon conversion of a circulating fluidized bed gasifier can be as high as 98–99%[310, 649]. Gasification systems can supply clean products for use as fuel or synthesis gases in environmentally friendly processes[649]. The similarity between gasification and direct combustion is that they perform better with low moisture content of biomass unlike for anaerobic digestion[310].

Upgraded biogas has methane content at least 90%, but generally 96% to 99%) and low levels of impurities [719]. Biomethane has similar chemical properties to methane and natural gas with purity directly proportional to the upgrading efficiency of the method. Biomethane facilities or installations have downstream applications like gas storage, and transportation, cooking and home heating, industrial use, and distribution through small-scale local natural gas pipeline grids.[696, 927]

13.5. Applications of Biomethane

Biomethane has superior properties compared to biogas and is an attractive substitute of natural gas. It has both industrial and domestic applications like use as cooking gas, cogeneration can be packed in containers/cylinders as compressed biomethane and can be injected to natural gas mains for distribution. The main challenge is the cost of processing which is a function of technology used. Bio-CNG, which is a methane-rich compressed fuel in the form of biomethane. Bio-CNG is made from pure biogas with more than 97% methane

composition pressurized to 20–25 MPa. Compressed bio-CNG is similar in properties to regular CNG in terms of its fuel properties, economy, engine performance, and emissions. Like regular CNG, bio CNG has high octane number, and yields high thermal efficiency. It can therefore substitute the regular compressed natural gas in gas pipelines and other applications including fuel for natural gas power plants[1, 35, 701]. Figure 13-1 shows various pathways for value addition and application of biogas and biomethane.

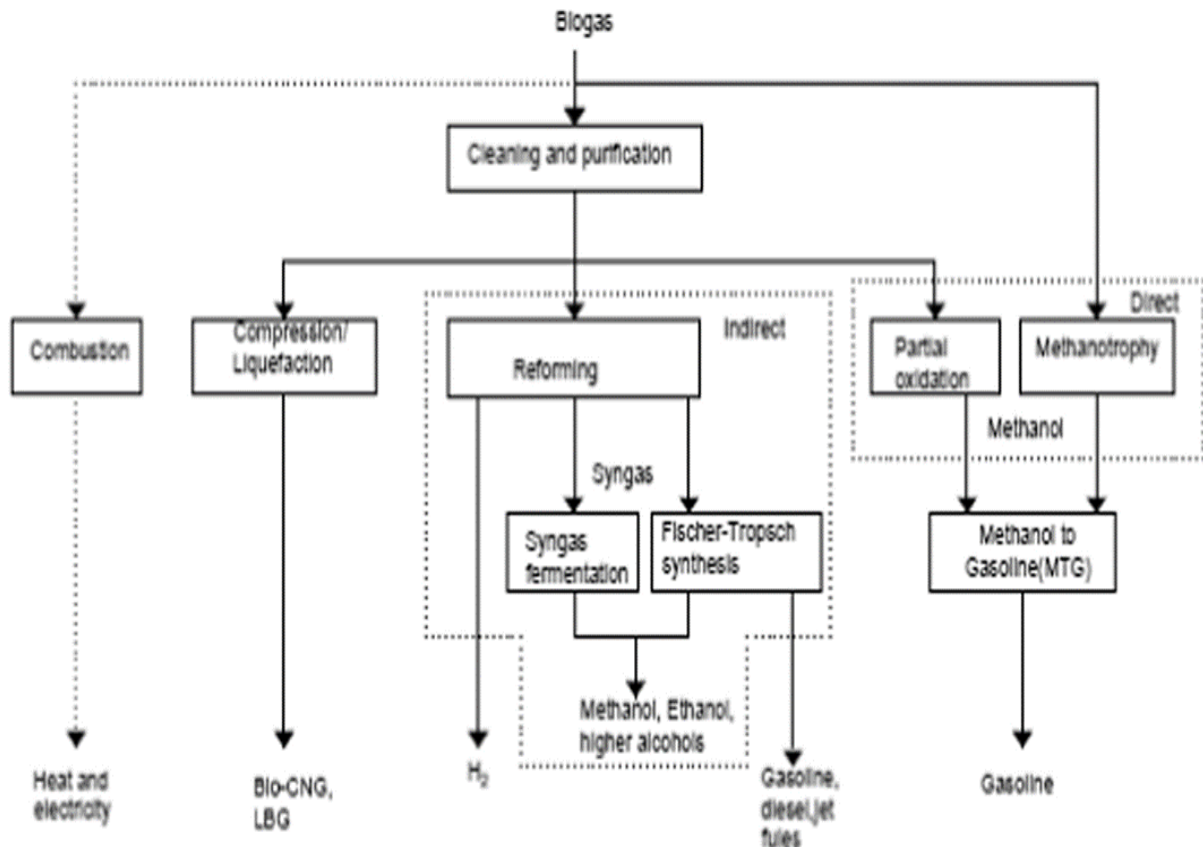


Figure 13-1: Applications of biomethane

From Figure 13-1 the various applications of biomethane as summarized include direct combustion for heat and power production, liquefaction to produce Bio-CNG and LBG, reforming to produce hydrogen, and syngas, partial oxidation to produce methanol fuel and further processing to produce gasoline, among other.

13.6. Hydrogen Production

Hydrogen is an ideal raw material for a sustainable energy transformation, but with the challenge being where and how to get hydrogen from renewable sources. Renewable hydrogen can be produced using renewable energy sources and usually produced via water electrolysis[928]. Biogas has applications beyond electricity and biomethane production, as

because, through steam reforming, it can be used to manufacture green hydrogen, in a process where a catalyst refines and separates the hydrogen from the gas stream[928]. The most common method used to manufacture hydrogen is by steam-reforming of natural gas, followed by pressure-swing adsorption to remove impurities. However, small reformers like those used for combined heat and power with biogas plants are in commercial operation[928]. The biogas has low heating coefficient due to high composition of carbon dioxide and water vapor interfere with the combustion process[928]. Upon removal of carbon dioxide and water molecules, the methane (CH_4) can be used for hydrogen synthesis and bio-fuel production. Methane can be split to hydrogen molecules (H_2) in a process that can be done in a steam/methane reformer. In the process, high pressure and temperature steam is combined with the methane (CH_4) to produces flow of hydrogen molecules and CO molecules[929].

It is through thermochemical processes of hydrocarbons that large scale hydrogen production is manufactured through the reforming process. Biomethane has significant potential application in hydrogen manufacture as a substitute of fossil natural gas as a raw material for reforming processes. The demand for renewable hydrogen production is set to grow significantly due to concerns over fossil fuels depletion and greenhouse gas emissions, and associated concerns over global climate change. The availability of capital, desired hydrogen amount and purity hydrogen and the composition of available biogas will influence the selection of reforming processes[282].

Biomethane has a significant application in fuel cell technologies for applications like power generation. Fuel cells can use hydrogen to generate electric power just like batteries as well as fuel for the fuel for powering fuel cars. Fuel cell technology in power generation is emission free and hence attractive [930].Biomethane can be used as a source for renewable hydrogen, for stationary fuel cells and power fuel cell electric vehicles (FCEVs). The Hydrogen-powered FCEVs are environmentally attractive since they have no tailpipe emissions other than making them extremely clean as transport option to fossil fuel powered vehicles [282].

Use of biomethane for hydrogen production can increase energy sustainability can be for energy applications like fossil fuels. Hydrogen can be manufactured by autothermal reforming (ATR), electrolysis or methane reforming (SMR) [281]. Biomethane can be used as a substitute of natural gas which will provide a hedge against growing demand for natural gas[282].

Hydrogen fuel can be used to reduce emissions from engines which are widely used in transportation. Hydrogen fuel cells promise to provide an alternative to internal combustion (IC) engines particularly due to the clean exhaust emissions, renewal nature of the fuel and higher efficiencies. Hydrogen fuel cell vehicles can achieve widespread acceptance except for existing challenges like waste heat removal in mobile applications[931].

13.7. Production of Biofuels from Biomethane

The transport sector is important since it accounts for about 14% of the global greenhouse gas emissions[166]. Liquefied biomethane is a feasible fuel for power plants and heavy tracks and can also be used as a raw material for production of other fuels and chemicals like methanol, dimethyl ether, and hydrogen fuel. Biomethane is currently used as a transport fuel many countries with benefits of lower environmental impact compared to fossil fuels and several other processed transport fuels [932].

Biofuels include the Bio-CNG which is compressed biomethane like (CNG) in properties with industrial, automotive, and domestic applications. The process needs removal of impurities likes water, N₂, O₂, H₂S, NH₃ and CO₂ to achieve composition of >97% CH₄, <2% O₂ at 20–25 MPa. Bio-CNG occupies less than 1% of the volume at standard conditions[932, 933].

Biomethane can also be used in the industry as transport fuel by liquefying it to at a high pressure re ranging from 0.5 to 15 MP. [4]. In the biological or chemical pathways, biomethane can be converted to methanol, diesel, liquefied petroleum (LPG) and gasoline. Methanol is produced by partial oxidation of methane as shown below.



In another method, methane is biologically converted from to methanol by using methanotrophic bacteria used in methanol production through the action of methane monooxygenase (MMO) enzyme [5].

Methanol can also be produced by reforming methane to syngas then followed by catalytic conversion of syngas to methanol as shown below [6].





Methanol can then be converted to gasoline through methanol-to-gasoline process. Biogas or biomethane can be processed to methanol through dry reforming, steam reforming, partial oxidation reforming, autothermal Reforming (ATR) and the Fischer-Tropsch (FT) Process. Synthesis gas (syngas) is the main product of biomethane reforming process. Syngas is a raw material for production of many long chain hydrocarbons [934]

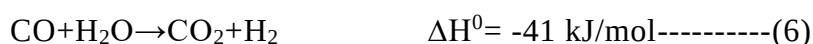
13.7.1.Dry Reforming

In dry reforming, CO and H₂ are produced by reaction of methane (CH₄) and carbon dioxide (CO₂). The process utilises two greenhouse gases (CH₄ and CO₂) making it very attractive. Unfortunately, the endothermic reaction reduces the of CO₂ emissions, since CO₂ emitted generate, the heat required for the reaction must be accounted for. Dry reforming is an efficient route for producing synthesis gas yielding a H₂/CO ratio close to 1[444] . The disadvantage of dryy reforming compared with steam reforming it produces lower syngas ratio (H₂/CO=1), The ratio of H₂/CO ratio is influenced by water gas shift reaction (WGS), which reduces the ratio due to reverse reaction that oxidizes hydrogen to water. In this process, the H₂/CO ratio is kept between 1 and 2 by partial oxidation of methane through feeding water. This enhances forward water gas shift reaction. The energy demand by the process is lower since partial oxidation is exothermic [934]. The temperature range for dry reforming process 700–1000°C[934].



13.7.2.Steam Reforming and Water Shift Reaction

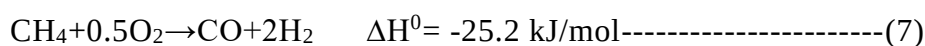
This process combines methane in biomethane with water vapor generate CO and H₂ in the in the presence of a catalyst. The process is endothermic and takes place between 650 and 850 °C, to produce hydrogen yield of 60–70%[444]. Steam reforming takes place between 700–900°C. The two-step chemical reaction is shown in 5 and 6 below.



The process of steam reforming is often followed by a water shift reaction to improve hydrogen generation.

13.7.3. Partial Oxidation Reforming (POR)

This process is used to produce hydrogen at reduced energy cost because the process is moderately exothermic compared to steam reforming which is highly endothermic. H₂ and CO are produced by the partial oxidation at atmospheric pressure and between 700 and 900 °C partial oxidation reforming. The H₂/CO ratio of 2 yield is achieved in full conversion with reduced soot formation. Methane reacts with oxygen to form carbon dioxide (CO₂) due to a decrease in CO selectivity. The combustion is strongly exothermic leading to formation of hot-spots in the reactor bed and coke deposition on the catalyst[444]. In this process, methane is oxidized to syngas as demonstrated in equation 7 below.



13.7.4. Autothermal Reforming (ATR)

Autothermal Reforming is a combination of two processes i.e., POR and SR in the presence of carbon dioxide. In Autothermal Reforming (ATR) partial oxidation takes place in the reactor to produce heat needed for steam reforming in the catalytic zone. The process does not need external heating and the reactor is easy to stop and restart. Compared to partial oxidation reaction, the hydrogen yield is higher and consumes less oxygen compared[444].

13.8. Upgrading Syngas

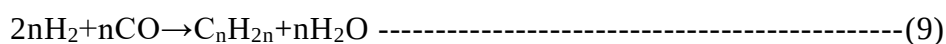
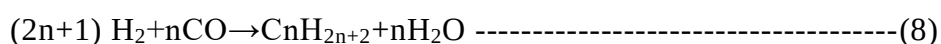
The Syngas produced from the dry reforming has carbon dioxide which should be removed before it is supplied to the Fischer-Tropsch reactor. Amine absorption has high selectivity for carbon dioxide. Other applications of this technology are separation of CO₂ from flue gases, natural gas cleaning and largescale upgrading of biogas. Common solvents used in the process are alkanolamines like monoethanolamine (MEA), diethanolamine (DEA) or methyldiethanolamine (MDEA) [935, 936].

13.8.1. Fischer-Tropsch (FT) Process

The Fischer-Tropsch (FT) synthesis, was name after the German inventors Franz Fischer and Hans Tropsch is a process used to manufacture liquid hydrocarbon fuels like coal-to-

liquids (CTL) and/or gas-to-liquids (GTL) based on source of syngas. [935, 936]. The biomethane and natural gas conversion to fuels via Fischer-Tropsch synthesis (FT-synthesis) is feasible at industrial scale[934]. The Fischer-Tropsch (FT) process is converts syngas to products like LPG, diesel, and jet fuels [935].

The Fischer-Tropsch synthesis (FT-synthesis) polymerizes the carbon and hydrogen atoms in syngas or biomethane to create long chain molecules. The process is run over iron or cobalt catalyst at 20-30 bars [14] in an overall exothermic process leading to polymerization of CH₂ to hydrocarbons with long chains called syncrude. The various reactions in Fischer-Tropsch process are summarised in equations 8 and 9 below.



Reactors used include multi-tubular fixed bed, circulating fluidized bed, fixed fluidized bed, and slurry reactor. The reactions for the slurry reactor conditions are 20-30 bar, and 200-300°C while the syngas H₂/CO ratio of 1-1.8[934, 935]. For high temperature synthesis, fluidized-bed FT reactors are used to generate light hydrocarbons in the form of gaseous hydrocarbons and gasoline and generally have higher output. The catalysts used are Fe and Co which are sensitive to sulphur compounds in syngas[935].

13.9. Biofuels from Biomethane

Various biofuels can be made from biomethane for the transport sector e.g. methanol, compressed biogas (CBG), hydrogen, liquid biogas (LBG), dimethyl ether and Fischer-Tropsch (FT) fuels[937]. Fuels can be produced by biogas upgrading to biomethane then compressing to make (CBG) or liquefying to make (LBG), or gasification to produce syngas for use in manufacture of hydrogen, methanol, DME and FT diesel [937].

13.10. Biomethane for Gas and Power Grids

In many countries, governments have come up with national support schemes to promote the biomethane market. Support mechanisms include feed-in support schemes, green gas products and quota obligations as market drivers in Europe. Biomethane production for many countries is based on organic waste as feedstock, but for Germany which dominates Europe's feed-in market is based on energy crops. In Germany, the main driver is the feed-in tariff for renewable electricity through the Renewable Energy Sources Act (EEG). Biomethane

support schemes mainly rely on mass balancing systems or ‘book and claim’-certificates. Existing mass balancing systems can contribute to international market development through the creation of common standards. As biomethane becomes popular and relevant in the energy systems, integration into power and gas grids and shift away from subsidies to markets and competition with natural gas will become major issues[938].

Biomethane should meet some standard specifications with respect to storage and transport before it can be practical injection into existing natural gas networks. The presence of various components in different concentrations make it difficult to inject biogas to the grid hence the need for upgrading. Pipeline designers should know the exact thermodynamic properties of a gas mixture are, particularly in terms of density, and heating value which may tend to vary greatly in biogas [475].

Biomethane has a very important role to play in the transition to renewable sources of energy. Demand based production of biomethane for power generation directly links the gas grid and the electricity grids which can help in balancing the power grid. The gas grid will shift from fossil fuel distribution to provide energy balancing service provider with short-term as well as seasonal storage options. There is increasing integration of decentralized biomethane feed-in into the gas grid for the gas grid infrastructure thus introducing new challenges. There are examples in Germany of facilities that feed in more biomethane to the local distribution network than the total discharge which leads to the need to compress the excess gas and transfer it to a higher level[938].

Production of biomethane from energy crops has a negative impact on agriculture. On the other hand, use of digestion residues as fertilizers close to biogas production site improves local nutrient cycles. Production of energy intensive nitrogen fertilizers and use of declining global phosphorous reserves can be avoided by use of bio-fertilizer from the digesters.

Biomethane is the most efficient biofuel in terms of fuel production equivalent per area of crop land needed and is therefore expected to a larger role in the fuel/energy market because of government support, growing use in NGVs and reduction in GHG emissions. There is growing awareness of biomethane and a shift in perception from regarding biomethane as a sub-branch of biomass production to an independent renewable energy resource. And legislation and strategies are recognizing biomethane as an independent energy resource[938].

The main sustainability challenge facing biomethane market is cost of subsidies and need for free market competition with fossil natural gas which can be accelerated if the market price of natural gas rises. The European cap-and-trade for greenhouse gas emissions GHGs is another driving factor for the future. Since use of biomethane omits GHG emissions, there won't be compensation or penalties in form of GHG certificates[938].

The evolution of biomethane markets is expected to create their own demand and supply and enable and exchange between different countries since the green gas product market opened to international trade. Each country has tended to create its own set of biomethane support schemes to address individual situations and therefore designed to address the priorities and challenges of specific countries. For biomethane market to grow, countries should open up their support schemes to biomethane imported from neighboring countries to encourage international trade in biomethane[938] .

13.10.1. Electricity from Biomethane

Biomethane can be used as fuel for power generation in various prime movers. They include internal combustion engines, gas turbines of varying sizes, fuel cells, among others. The efficiency can be improved through combustion and conversion in set ups like cogeneration and tri-generation schemes[62].

Diesel engines can run on biomethane as a direct substitute of natural gas. Biomethane used can made from biogas upgrading or gasification and methanation schemes [477]. Diesel engines would perform efficiently whether using pure diesel or when running in dual fuel mode as long as the calorific value of fuel is controlled [477, 939].

Electricity from biomethane can be used directly onsite to avoid or limits electricity imports from the grid while excess generated electricity within the design of decentralized power generation systems using a wide range of prime movers for the electric generators e.g., turbines, internal combustion engines, fuel cells, etc. Biomethane can be converted to hydrogen fuel for wide renewable applications or used in fuel cells for direct conversion. Various pathways for use of biomethane for power generation are summarized in Table 13-1.

Table 13-1: Summary of biogas to electricity conversion systems and technologies

Device /	Application	Remarks

technology			
1	Fuel cell	Generation of electricity	Very efficient, reliable but expensive
2	Hydrogen production	Biomethane can be converted to hydrogen for use as combustion fuel or electricity and process chemicals.	Renewable hydrogen process is its biogas or methane. Hydrogen is manufactured by dry reforming, steam reforming, or hydrolysis
3	Bio-methanation	Biomethane can be fed to natural gas supply as substitute for natural gas	Renewable replacement of fossil natural gas is feasible with use of biomethane
4	Diesel engine	Biomethane can be used as a diesel engine fuel in either dual fuel mode or pure gas engines	Diesel engines have more fuel flexibility and efficiency and can easily use easily use biofuels as fossil fuel substitutes
5	Gas/petrol engine	Biomethane can be used as a fuel for petrol or gasoline engines with little or no modification	Less efficient than diesel engines but are easier to convert to biogas fueled engines.
6	Stirling engine	Stirling engines are also called hot air engines.	Stirling engines have fuel flexibility and can run on a wider range of fuels
7	Gas turbine	Based on size, gas turbines can be micro, small, and large gas turbines in open, closed, or combined cycle configuration	Turbines are simple in construction, are versatile and can use raw biogas as well as biomethane and easy to operate.
8	Cogeneration	In cogeneration, biomethane is burned to simultaneously produce useful heat and electricity.	Cogeneration with biomethane as a fuel can be applied on various conversion systems like Stirling engines, diesel engines, gas turbines,

		hydrogen, and fuel cells to increase system efficiency
9	Trigeneration	Trigeneration refers to generation of electricity and both heating and cooling from same fuel/energy resource simultaneously Trigeneration is the most efficient conversion system but more complex and expensive

From Table 13-1, biomethane can be used through various conversion technologies with varying characteristics in thermal and electricity generation. The conversion can be done in cogeneration, trigeneration and open conversion systems. Prime movers that can use biomethane include internal combustion engines, gas turbines, fuel cells, and Stirling engines as well as production of fuels for application in transport, heat, and electricity generation.

In the transport sector, biomethane has a double role to play in emissions reduction i.e., as a direct fuel substitute of fossil fuels and as feedstock for production of biofuels/chemicals through the Fischer-Tropsch (FT) Process e.g., diesel, jet fuel, and gasoline, and through reforming processes to produce hydrogen and methanol.

Biomethane production and use has less environmental impact but is still associated with some greenhouse gas emissions like CO₂, CH₄ and N₂O whose quantities depend on the technology applied and the source of biogas or feedstock used. Biomethane use can reduce the negative environmental impact and pollution potential while anaerobic digestion and gasification used to produce biogas and syngas can be used for hygiene and of bio wastes further keeping the environment clean and healthy [473, 484, 485].

13.10.2. Environmental Impact of Biomethane

The use of farm derived feedstock provides large potential for renewable biomass resource to produce biomethane. Existing management practices like spreading in fields can increase emissions from agricultural wastes. Through anaerobic digestion, farms get on-site waste management which produces biogas energy and organic fertilizer besides sterilization benefits for disease causing pathogens.

Assessment of greenhouse potential of farm-derived biomethane yields different results based on feedstock type, technology configuration and facility management practice. Bio-waste or agricultural wastes can yield negative emissions by anaerobic emissions if traditional management is considered. The use of N-fertilizer in crop silage leads to higher GHG balance, the dominant emission source. The fugitive methane emissions derived from biogas production and upgrading reduces the GHG benefits of anaerobic digestion. It is therefore necessary to have well managed and operated biogas production and upgrading facilities[388, 940].

Studies have shown that upgrading biogas consumes about 20% of the energy in biogas using current technologies and most of the energy is applied in compression. [927]. This effectively reduces the net energy value of biomethane. Table 13-2 presents a summary of the well to wheel greenhouse emissions from biomethane and fossil fuels.

Table 13-2: Well To Wheel (WTW) GHG emissions in gCO₂eq/km[927]

Fuel type		WTW gCO ₂ eq/km	emissions	Remarks
1	Petrol/gasoline	164.0		Has high environmental impact
2	Diesel	156.0		Cleaner than petrol
3	Compressed natural gas (CNG)	124.0		Cleaner than petrol and diesel
4	Bio-CNG (20%)	100.0		Less impact than natural gas
5	Bio-CNG (100%)	5.0		Cleanest

From Table 13-2, it is noted that compared with bio-CNG, compressed natural gas, diesel, and gasoline fuels, biomethane has the least environmental impact based on the wheel to wheel (WTW) values of emissions.

13.10.3. Lifecycle Assessment and Sustainability of Biomethane

Biogas upgrading involves purification processes aimed at increasing methane content of biogas that is like natural gas. The environmental assessment, based on the Life Cycle Assessment (LCA) method, of different upgrading technologies will help in the identification of the environmental characteristics of biomethane and improvement measures. The LCA of biomethane production from waste feedstock, using the SimaPro software comparing several upgrading technologies like membrane separation, cryogenic separation, pressure swing adsorption, chemical scrubbing, high pressure water scrubbing and the on-site cogeneration of electricity and heat, that include environmental benefits derived from the substitution of fossil-based products. Indicate a better environmental performance of the cogeneration option. Studies show an average improvement of close to 76% compared to conventional cogeneration. Membrane upgrading technology shows the best environmentally convenient results compared to other biogas upgrading methods [941, 942].

Biogas upgrading by removing CO₂ and other contaminants enables biogas fuel to attain the specifications required for injection in the natural gas grid and application as fuel for vehicles. The process facilitates conversion of wet biomass into a perfect substitute of natural gas. Biogas upgrading involves the removal of CO₂ using various techniques, but the most diffused method is water scrubbing. The CO₂ can also be directly recycled into methane through a high-temperature co-electrolysis process followed by methanation to increase biomethane yield. The environmental impacts of two pathways for biomethane production compared in the framework of the Life Cycle Assessment (LCA) methodology shows that due to high electricity demand, the electrolytic process where electricity source is not close to 100% renewable is unfavorable [943].

Several have been carried out aimed at evaluating the life cycle environmental impacts associated with the power generation from biogas produced by anaerobic digestion of agricultural products and waste. Studies on the anaerobic digestion using tomato waste, maize silage, slurry, and tomato waste as feedstocks and for cogeneration applications suggested that systems using animal slurry offer best options, except for ecotoxicity to marine and terrestrial environment. The studies also indicate that it is more feasible to have smaller plants that use slurry and waste rather than big plants using maize silage to operate efficiently. Electric power from biogas is environmentally more sustainable than grid electricity for many biogas schemes. However, compared to natural gas, biogas electricity is not always the best option in terms of impacts. Biogas also has higher impacts than other

renewables, like solar photovoltaics, wind and solar. Overall, though, biogas electricity can help minimize the GHG emissions relative to a fossil-intensive electricity mix, although some other impacts may increase. Further analysis shows that, if the main objective is to mitigate climate change, then other renewables like wind, solar and hydro offer greater potential to reduce GHG emissions than biogas. However, by cogeneration where heat is used, the environmental sustainability of biogas will significantly improve particularly in terms of the global warming potential, summer smog, and the depletion of ozone layer and abiotic resources. Avoiding open digestate storage minimizes methane emissions while regulating digestate spreading onto land help minimize emissions of ammonia and related environmental impacts[944].

Studies were carried out by [942] on the environmental and economic aspects of common biomethane production methods namely membrane separation, chemical absorption with amine solvent, water scrubbing, and pressure swing adsorption a life cycle perspective using data from the Italian existing plants. The results of the study showed that all the biogas upgrading options are fully sustainable, and in particular, the membrane separation technique showed the best performances, although in some cases with little differences [942].

Biogas upgrading to biomethane consumes about 20% of the biogas energy using existing conversion technologies mainly in compression. [927]. Table 13-3 is a summary of the well to wheel greenhouse emissions from biomethane and fossil fuels.

Table 13-3: Well To Wheel (WTW) GHG emissions in gCO₂eq/km[927]

Fuel type		WTW gCO ₂ eq/km	emissions	Remarks
1	Petrol/gasoline	164.0		Has high environmental impact
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3	Compressed natural gas (CNG)	124.0		Cleaner than petrol and diesel
4	Bio-CNG (20%)	100.0		Less impact than natural

			gas
5	Bio-CNG (100%)	5.0	Cleanest

From Table 13-3, it is noted that biomethane has the least environmental impact based on the WTW values of petrol, diesel, compressed natural gas when used as a fuel substitute for fossil fuels namely petrol, diesel, and natural gas.

Studies of the current state biomethane production suggests a current production potential of more than 1.9 billion m³/yr, with commercial initiative in Europe alone being more than 645, in 2017, most of them being in Germany. Way forward into the future new biogas plants will have to be equipped with upgrading units, that will foster cost reduction and a parallel consolidation of the operation plants availability. Biomethane production is projected to grow and reach 18 billion m³/yr in 2030; based on improvement of already installed biogas plants, with increased use of feedstock like municipal solid waste (MSW.) This potential is about 10% of natural gas projected demand for the EU's in 2030[919]

13.10.4. Summary, Discussion and Suggestions

Biogas is versatile fuel with low emissions and other benefits when used as a renewable energy resource. Biogas is generally produced by anaerobic biodegradation of organic wastes whose process benefits are production of energy and waste treatment, sterilisation, and disposal for a safe and clean environment. Biogas has noncombustible and undesirable components like moisture, carbon dioxide, siloxanes, hydrogen sulfide, siloxanes, hydrocarbons, oxygen, ammonia, oxygen, carbon monoxide and nitrogen whose presence is undesirable as they reduce the calorific value of biogas and create operational problems in the energy systems. Biogas can be cleaned to produce a safer and cleaner fuel and while upgrading mainly by removal of carbon dioxide generates biomethane whose properties are like natural gas and hence its renewable substitute to fossil methane or natural gas. Both biogas and biomethane have a wide range of feasible thermal energy and electricity generation applications.

Many technologies for biogas cleaning and biomethane production are available as well as technologies for conversion of biogas and biomethane to heat or thermal applications and electricity generation. Conversion systems and prime movers available include diesel and petrol engines, gas turbines, Stirling engines, use in renewable or green hydrogen production,

conversion in fuel cells, and biofuel production as feedstock effectively supplementing and substituting the use of fossil fuels. Through application in grid electricity generation and supply, biogas and biomethane has a critical role in decentralized generation and rural electrification effort and hence the energy transition. Therefore, biogas and its derivative biomethane present significant opportunities for direct and indirect use in thermal/ heat, cooling, and power generation in the energy transition [472, 945].

Biomethane can be produced through gasification or anaerobic digestion and upgrading of biogas which are technically and economically different. Anaerobic digestion involves decomposition of complex organic matter in absence of oxygen by action of anaerobic microorganisms, in a low energy demand of heat and electricity making it highly energy efficient[488]. However, the anaerobically produced biogas has got a high fraction of carbon dioxide which has to be removed through various upgrading techniques to produce biomethane with purity of biomethane i.e. >95vol%. The main challenge with biogas upgrading to produce biomethane is the high cost of common technologies like water scrubbing, pressure swing adsorption, chemical absorption etc. mainly because of the use of either energy, chemicals, or both.

Gasification of biomass is another efficient pathway for biomethane production which starts with the production of syngas. Syngas can be used directly to produce power, heat, and fuels, such as hydrogen and ethanol, but can be processed to produce biomethane. However, methane content in syngas is low and normally requires a methanation process which converts CO and H₂ to CH₄. Water-gas-shift (WGS) process is also needed before methanation, to control the C/H ratio of syngas. Combination of WGS and methanation processes reduces the overall efficiency of gasification, complex system configuration and higher investment and operation costs. The advantage of gasification over anaerobic digestion is the ability of largescale production of biomethane. Gasification and anaerobic digestion principally use different but there is a general a trend to apply gasification to recover energy from waste like as the municipal solid waste, agricultural waste, sludge, which can still be anaerobically digested[488].

Many studies have been undertaken on the anaerobic digestion integrated with biogas upgrading and biomass gasification integrated with methanation; but little attempt has been made at making a comprehensive comparison about two approaches in biomethane production making it difficult to identify the best method for biomethane production from the

energy output and conservation perspective making the two technologies equally available for exploitation for now. [488].

The global market for biomethane is classified or segmented by feedstock type, the production methods, biomethane applications, distribution by region, and the landscape of competition in the market. Based on feedstock type, biomethane market can be further divided into animal waste, agricultural waste, animal manure, organic household waste, feedstock from energy crops, etc. Based on production method, the biomethane market is segmented into gasification sources and fermentation process. Based on application, the biomethane market can be segmented into power generation, automotive applications, domestic applications, industrial applications among others. Segmentation by geographical or regional distribution can divide the market into regional markets like EU, North American region, Africa, Sub-Saharan Africa, European region, South American region, Asia Pacific region, and Middle East & Africa regions.

The fermentation process is expected to be the largest contributor to the production method segment of the biomethane market and lead in terms of revenue shares of the market in future. This is because of increased inclination of the production sector towards ecologically and economic and ecological superior methods of biomethane production because of growing sustainability concerns and concerns over degrading environment and depletion of the ozone layer causing life threatening consequences hence the growing interest in fermentation process of production of biomethane. As opposed to gasification[946].

This study shows significant potential of biogas production and technology to convert biogas to biomethane which has wider applications as an energy resource compared to biogas. Biomethane can be used in the production of industrial chemicals and fuels as a feedstock and can be used in hydrogen production and direct power generation in fuel cells, substitute for natural gas and combustion fuel for heat and power generation as well as a fuel for transport.

The feasible technologies for production of biomethane are biomethane from biogas upgrade, natural gas by power-to-gas from renewable electricity and CO₂ and Synthetic Natural Gas from biomass gasification. The power-to-gas technological pathway uses the peaks of renewable electricity to produce hydrogen and use it to fix carbon via methanation reaction . while synthetic natural gas is made by thermochemical processes[919].

Application of biological techniques has increased because of their low cost and increasing efficiency in the removal of H_2S , but the physical-chemical technologies currently dominate the market for biogas cleaning with H_2S adsorption on activated carbon being the most used process to remove H_2S in biogas. Use of salts or iron oxides in situ is a common practice for cleaning biogas for heat boilers while bio filters are common in H_2S removal for use in combined heat and power (CHP) units in heat and power generation.

To attain very low concentration of H_2S , with high purification for biomethane production, require H_2S removal often in combination with removal of CO_2 . Commercially available technologies for purification of biogas are primarily meant for CO_2 removal, but they can remove other impurities. Pressurized water scrubbing is the most used technique for removal of CO_2 from biogas. The amine absorption method is preferred for use in smaller biogas production and in applications with cheap heat sources while membrane permeation method has grown, because of availability of highly selective and low-cost polymeric materials. Circumstances that may be unique or specific to a project and raw biogas capacity may significantly affect the cost of different upgrading technologies.

Systems that enable removal of CO_2 and application in other processes help reinforce the sustainability of biogas production and the concept of circular bioeconomy and should be encouraged. An example is biomethanol production systems integrated with biogas production and purification units which increase the economic value of the process and reduce environmental impact of the process. Carbon dioxide from biogas upgrading together with H_2 , from electrolysis through electricity from renewable sources are sustainable raw materials for production of renewable methanol in a biogas plant.

There is globally growing significance of renewable fuels that has forced countries to find sustainable alternatives to fossil fuels, making biogas stand out as a very important alternative fuel. Biogas can be used to produce electricity, heat, synthetic biofuels and can be upgraded to produce renewable natural gas as a substitute of fossil natural gas. The level of cleaning or treatment of raw biogas depends on the specific application. The physicochemical methods of biogas upgrading which are based adsorption, absorption, chemical reaction, cryogenic and membrane separations currently dominate the biogas treatment and upgrading market. Biogas upgrading process begins with cleaning of raw biogas to remove contaminants like hydrogen sulfide, from biogas. The various processes differ in energy consumption, initial capital, purity, and losses of methane. The main objective of upgrading is to remove carbon dioxide

and raise the calorific value of biomethane produced biomethane. Biomethane is generally less competitive than natural gas due to the high costs of making biomethane from biogas.

13.11. Biogas Cleaning

The cleaning of biogas methods available are many and significantly different from one another in terms of process design and setup, design principles, supporting materials, final product quality, cost, and energy requirements as well as handling of raw biogas. The Process selection and control is guided by raw biogas composition, availability of resources like e.g., water, electricity and space, and final product quality in terms of methane purity and composition[360, 947].

13.12. Biogas Upgrading Methods.

The conversion of biogas to biomethane can be significantly improved by use of a combination of a wide range of methods from biological and physicochemical processes and adaptation of technologies from other fields like advanced oxidation processes or anaerobic phototrophs. The treatment of biogas can theoretically start with biological methods like chemotrophic or phototrophic for removal of H_2S then continue for upgrading using physicochemical methods which are more efficient [945]

Water scrubbing is a biogas upgrading process that remains popular, because of its simplicity, it is cheap and does not need additional chemicals. The use of custom-tailored and biodegradable DESs makes organic physical scrubbing an attractive option to achieve high methane purity. The novel solid adsorbents (e.g., MOFs) or improving the sorbent design like honeycomb structures raises the attractiveness of PSA/VSA for biogas upgrading while cutting down the cost and the size of adsorption column. The chemical absorption system with super acid solvent simultaneously eliminates non-methane volatile organic compounds, H_2S , siloxanes, and part of CO_2 [945].

Biogas upgrading mainly involves the removal of carbon dioxide from raw biogas using various methods whose features and characteristics are summarized in Table 13-4.

Table 13-4: Performance of various upgrading methods [947, 948]

Method/ Process	CH ₄ pur ity (%)	CH ₄ losses	Other abilities	Energy consumpti on–raw	Energy consumpti on–clean	Capita l Costs	O& costs(€/k	M

s			(%)		biogas (kWh/Nm ³)	biogas (kWh/Nm ³)	(€/kW h)	Wh)
1	Pressure swing adsorption	95–99	< 4	Can remove H ₂ S, N ₂ , and O ₂	0.23–0.3	0.3–0.9	255–831	0.92–6.50
2	Physical organic scrubbing	95–98	< 4	Can remove H ₂ S, and NH ₃	0.2–0.3	0.4–0.6	510–969	0.92–1.05
3	Chemical absorption scrubbing	95–99	< 1	Can be contaminated by H ₂ S	0.05–0.15	0.05–0.25	264–438	1.15–1.92
4	Water scrubbing	95–98	< 2 (8–10 non-optimized operation)	Can remove H ₂ S	0.25–0.3	0.3–0.9	357–731	0.47–0.97
5	Membrane separation	82–99	< 5	Can remove H ₂ S, N ₂ , and O ₂	0.18–0.21	0.14–0.26	305–367	0.79–5.50
6	Cryogenic separation	> 97	< 1	N/A	0.2–1.05	0.42–1.54	394–960	4.8–7.10

From Table 13-4, it is noted that there are various methods for biogas upgrading with different performance characteristics in terms of methane purity, methane losses in the process, energy requirements, capital costs and cost of operation and maintenance which can be used as a selection criterion.

13.13. Summary of Applications of Biomethane

Biomethane, also called renewable natural gas is chemically like natural gas and hence it is a substitute fuel for fossil natural and can be fed into the gas transport and distribution networks. Biomethane is used for power and heat production for domestic and industrial use and as a fuel for the transport sector.

The use of biogas has many environmental benefits with upgraded biogas having similar properties to natural gas. Biogas has thermal, electrical and industrial applications [472]. Biomethane applications which are often like those of biogas are summarized in figure 112.2 below.

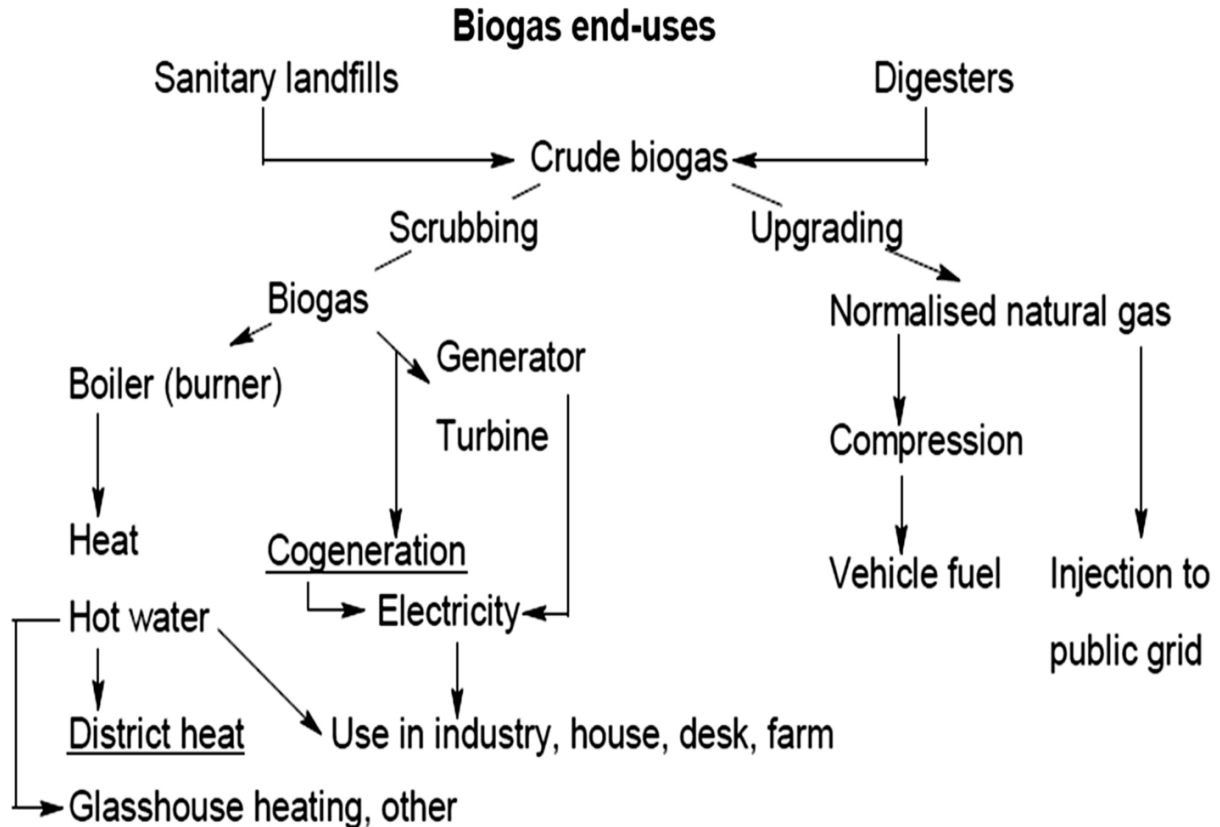


Figure 13-2: summary of biomethane and biogas applications in the energy transition

From Figure 13-2, it is noted that biomethane can be used directly for cooking, and lighting, power generation, cogeneration heating of glasshouses, vehicle fuel, energy for fuel cells and injection to the public gas grid for multiple applications in domestic and industrial applications. Biomethane can be used for production of other fuels including the Fischer-Tropsch (FT) fuels. Biomethane can be used in methanol fuel production and can be compressed and packed as Compressed biogas (CBG) and liquid biogas (LBG) for many direct and indirect application as fuels in heat and power generation. Production of bio-CNG and bio-LPG from biomethane widens its applications as direct substitute for natural gas.

Biomethane can be used in manufacture of fuels by cleaning, and purification before reforming to syngas, as well as by partial oxidation to produce methanol which is used to manufacture gasoline. Syngas is used in the production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process.

13.14. Summary of Biogas Upgrading Techniques.

With increase in fossil fuel prices and environmental concerns, biogas upgrading for methane production has generated significant attention as a feasible substitute for natural gas and other fossil fuels applications[34, 386, 387]. Various upgrading technologies are currently available for use in biomethane production. These methods and technologies include Pressure Swing Adsorption (PSA) and Temperature swing (TSA), absorption techniques, Membrane separation, biological upgrade techniques, cryogenic separation [34, 472].

The study has identified five main biomethane production processes through biogas upgrading. The techniques are pressure swing adsorption which has an option of temperature swing adsorption, absorption technics based on amine, membrane separation, cryogenic separation, and biological separation. The various biogas upgrading methods are summarized inTable 13-5.

Table 13-5: Summary of Biogas upgrading techniques.

Bio	Advantages and applications	Limitations
methanation		
method		

1	Pressure Swing Adsorption (PSA) and Temperature swing (TSA)	PSA and TSA work by selective adhesion of one or more components of the mixture, on the surface of a micro-porous. The processes have low needs, use no chemicals, no water consumption by process, regenerative use of water and have no microbial contamination and impurities	The main limitations are the pre-treatment requirement and extensive process control making the process expensive. The process requires pretreatment to remove H ₂ S making it complex and expensive
2	Absorption techniques	Absorption techniques purification and enrichment processes are based on the solubility of constituent gases in biogas in a selected liquid	The main limitation of these technique is that it requires significant plant size to achieve high final concentration of methane
3	Membrane separation	Membrane are selectively permeable barriers, designed allow some molecules to pass through but stop or block others driven by pressure, temperature, relative concentration, electric charges of the molecules. Besides upgrading of biogas by removal of CO ₂ , the process also removes H ₂ S and H ₂ O in a relatively simple construction and process and with no chemical consumption	The technology is expensive and has low reliability. High maintenance and operation costs and the process is Complex. The method Can achieve methane purity by removing over 98% CO ₂ .The process becomes unstable over the long term, requires pretreatment, many are required even though simple to achieve high methane purity.
4	Cryogenic separation	The process is used to produce Bio-LNG and attains high methane purity and requires no chemicals. Also produces CO ₂ with high purity that can be	The process is relatively expensive with high capital and operating costs, has high energy requirements by process equipment like compressors and heat exchangers.

		applied in other value addition processes. biogas at high. Less energy can be used to produce liquid biomethane	The process also requires pretreatment to remove hydrogen sulfide (H ₂ S) and water vapor (H ₂ O) prior to the separation
5	Biological upgrade techniques	This technique has low investment requirements and operates. They are also easy to operate and have no chemical inputs making them safe and clean.	The hydrogen sulfide concentration remains high and excess O ₂ /N ₂ requires additional cleaning.

From Table 13-5, it is noted multiple biogas upgrading techniques are available for biomethane production. The methods include pressure swing adsorption (PSA) and temperature swing (TSA), absorption techniques, membrane separation, cryogenic separation, and biological upgrade techniques. The two methods of biomethane production are through biogas upgrading or by biomass gasification followed by methanation process. Both methods have similar efficiencies in biomethane production in terms of energy output and conservation perspective, but the two approaches have fundamental differences in process equipment, and the cost of the output varies[296, 322].

The various biogas cleaning and upgrading technologies are summarized in Figure 13-3.

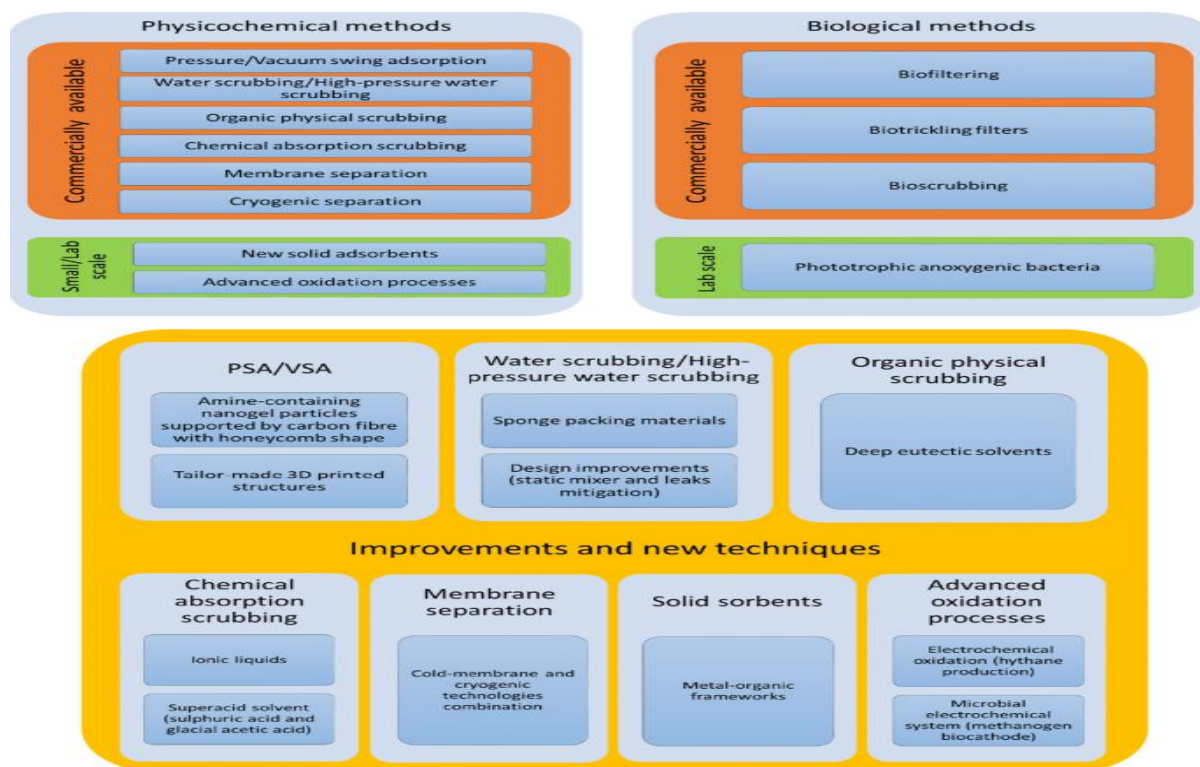


Figure 13-3: Summary of biogas cleaning and upgrading techniques.

From Figure 13-3, it is noted that various methods are available for biogas purification and upgrading. Commercially available physiochemical techniques include pressure/vacuum swing, water scrubbing, organic physical scrubbing, membrane separation and cryogenic separation. Laboratory scale physiochemical methods include new solid adsorbents and advanced oxidation processes.

Factors to consider in the technology or process selection include the gas quality requirements, costs, energy consumption, methane losses, and capacity requirements. Biological methods that are commercially available include bio scrubbing, bio trickling and bio filtering with phototrophic anoxygenic bacteria method still at laboratory scale. The physicochemical processes are more developed and widely used compared to many biological methods which are still new and not yet commercialized, but they offer significant huge potential in terms of efficiency, feasibility, and technological easiness. The main limitations facing biomethane production are the high costs of the process while many biological processes are still under research and development.

12.4. Status and Progress of Biomethane to Electricity/Energy Conversion

The various pathways for use of biomethane in the energy transition are summarized in Table 13-6.

Table 13-6: Summary of biogas to electricity conversion systems and technologies

Method/ process	Device / technology	Remarks
1 Chemical-electrical	Fuel cell	Very efficient, reliable but expensive
2 Chemical-electrical	Hydrogen	Renewable hydrogen process if its biogas or methane is from renewable resources. Hydrogen is difficult to handle and transport.
3 Chemical	Bio methanation	Renewable replacement of fossil natural gas
4 Thermal- electrical	Diesel engine	Diesel engines are more efficient than petrol engines and have more fuel flexibility hence can easily use biofuels.
5 Thermal-electrical	Gas/petrol engine	Less efficient than diesel engines but are easier to convert to biogas fueled engines.
6 Thermal- mechanical- electrical	Stirling engine	Stirling engines have fuel flexibility and can run on a wider range of fuels
7 Thermal- Mechanical Electrical	Gas turbine -	Turbines are versatile and can use raw biogas in uncleaned form. They are light and simple in construction, easy to operate but need skilled manpower.
8 Thermal- mechanical- electrical	Cogeneration	Cogeneration improves the overall system efficiency. Stirling engines, diesel engines, gas turbines, hydrogen and fuel cells can all be operated on cogeneration mode.
9 Thermal- mechanical	Trigeneration -	Trigeneration is the most efficient conversion system but more complex and expensive

From Table 13-6., it is noted that biomethane energy can be converted through various technologies and prime movers for heat and power generation. They include combustion in gas turbines, internal combustion engines, Stirling engines, use in fuel cells, and feedstock for hydrogen and biofuel production.

Biomethane has got two pathways for emissions reductions in the transport sector from the transport sector which account for close 14% of all anthropogenic greenhouse gas emission. They are direct use as a fuel direct substitute of natural gas and petroleum i.e., petrol and diesel, or biomethane can be used as a material feedstock for the manufacture of biofuels/chemicals through Fischer-Tropsch (FT) Process. The products of the process include jet fuel, gasoline, and diesel. Biomethane can be used as feedstock in the reforming processes like dry reforming, steam reforming, partial oxidation reforming and autothermal reforming to produce hydrogen and methanol which can be applied as a fuel in fuel cells with very minimum carbon value. Biogas derived transport fuels have very low emissions and, in some cases, have a negative carbon value.

Biomethane has a wide range of applications in heat and electricity generation, and industrial applications as a raw material. The utility of biogas is significantly improved by cleaning and upgrading. Biogas upgrading can be significantly improved by combining a wide range of methods ranging from biological and physicochemical processes and adaptation of technologies in the field of advanced oxidation or anaerobic phototrophs.

Biomethane is an ideal substitute for natural gas in the production of green hydrogen. Hydrogen has a potential to play an important role in decarbonizing hard-to-electrify sectors of the economy, e.g., long-distance trucks in transport, aviation, and heavy manufacturing industries. Hydrogen fuel can be used to reduce emissions from engines which are widely used in transportation. In the transport sector emissions, hydrogen can provide an alternative to internal combustion (IC) engines particularly due to the clean exhaust emissions, renewal nature of the fuel and higher efficiencies. Hydrogen fuel cell vehicles can achieve widespread acceptance except for existing challenges like waste heat removal in mobile applications.

13.15. Policy and Legal Measures and Implications

There is a need to develop policy measures that encourage adoption of bio methane and hydrogen from renewable sources in power generation and other energy applications. Attractive feed in tariffs can be used to promote investment in grid connected bio methane-based power. Feed-in tariffs refer to minimum prices guaranteed by the power utilities and governments over a defined period for the kWh generated and supplied to the grid or directly consumed. Countries like Italy, France, Austria, and United Kingdom have tariff incentives for investors in biogas and bio methane powered electricity.

Another incentive measure is the premium tariffs, that establish a premium on the power price. Power producers obtain revenue by selling energy in the power market and an additional one that is related to the premium tariff. Premium tariff is a technology-specific subsidy for units of renewable energy at a fixed, pre-set, floating rate. The exemptions or reductions are additional support systems to investors in renewable hydrogen and natural gas projects to promote investment [919].

The production of biomethane and upgrading technologies evolved significantly especially with the introduction of the EU landfill directive in 1999 which banned landfilling of organic wastes the EU or face a penalty of €75/t. Since a significant number of renewable energy technologies cannot effectively compete with conventional technologies, the technology needs to be economically viable through policy and legal measures. Likewise, biomethane needs initial policy support to kick-start the industry in any country [949].

13.16. Conclusions

Biogas, which is a product of the anaerobic digestion of biomass has many applications as a renewable energy resource. Biogas is a promising solution to the environmental and energy challenges facing mankind. However, in its raw form, its applications and energy content are limited due to the presence of some undesirable components which need to be removed to improve the thermal and chemical properties of biogas fuel.

Biomethane is upgraded form of biogas with wide range of applications like replacement of fossil fuels for heat and steam, electricity generation and cogeneration, vehicle fuel, and feedstock for manufacture of bio-based chemicals and substrate in fuel cells, starting reactants in chemical processes, natural gas substitute for industrial and domestic application as well as injection to natural gas grids. The Biomethane technology market is a promising venture globally mainly due to the existence of mature production, conversion technologies

and applications. Biomethane has significant flexibility for domestic and industrial scale production and use and is promising to be a leading economical alternative to produce renewable bioenergy.

The treatment of biogas can theoretically apply biological methods like chemotrophic or phototrophic to remove H_2S then start upgrading using more efficient physicochemical processes. Purification of biogas is generally a high energy intensive process. Biological methods of upgrading biogas open new horizons for integration of different forms of renewable energy besides electricity, storage advances and decoupling bioenergy production from the availability of biomass resources. The water scrubbing can simultaneously remove CO_2 , H_2S , NH_3 and dust but consumes a lot of water. On the other hand, the pressure swing adsorption technique requires biogas pretreatment since water and hydrogen sulfide can damage the adsorbents but has low energy requirement. The advantage of Amine absorption is low methane loss and produces high quality CO_2 , although it has high energy consumption. The advantage of the membrane permeation systems is their compactness and ease of operation but yields a relatively low methane (CH_4) purity.

Biomethane can be used for power generation using various available conversion systems like gas turbines, micro turbines, diesel engines, petrol engines, and Stirling engines. Other applications of biomethane production of hydrogen used in fuel cells or combustion, manufacture of transport fuels for direct heat and power generation (CHP), compression to CNG and LPG and injection to gas grids as a substitute of natural gas, reforming to produce syngas, partial oxidation for methanol production and gasoline and a feedstock in the Fischer-Tropsch process to manufacture chemicals, gasoline, diesel, and jet fuels. The pathways for production of fuels from biomethane are compressing to produce (CBG) or liquefying to make (LBG), hydrogen production, methanol, production, DME and FT diesel. The main challenge facing biomethane production and sustainability is the high cost of production. Through an appropriate choice of a combination of cleaning and upgrading methods based on methane purity energy can be saved and reduce methane loss, in large scale operations.

13.17. Recommendations

Biomethane has an important role to play in the energy transition especially as a substitute of natural gas. However, it is necessary to develop the technology of biomethane production to reduce costs and efficiencies and make it cost competitive with natural gas through policy measures and research and development.

CHAPTER 14:

HYDROGEN ENERGY

14. Overview

Hydrogen has emerged as a sustainable energy source for the energy transition, being vast and clean as a fuel. The contents of this chapter are published in [309, 666] on hydrogen production and applications in the energy transition. Production technologies for hydrogen are viable and commercially available, while some are still under development. In hydrogen is a renewable secondary energy source, and feedstock, and tool to meet greenhouse gas emissions targets and promote economic decarbonization. The unique properties of hydrogen make it a powerful enabler for energy transition, benefiting the energy system and end-use applications. Hydrogen gas has significant potential to play an important role in decarbonizing hard-to-electrify sectors of the economy, like long distance trucks in transport, aviation, and heavy manufacturing industries.

Hydrogen and fuel cell technologies will enable the transition to a clean, low-carbon energy system resulting in significant reduction in related greenhouse gas emissions and improved air quality. Green hydrogen energy provides clean energy, and the comprehensive utilization of hydrogen energy is crucial for the low-carbon transformation of the power sector. The production of hydrogen through water electrolysis powered by renewable energy reduces carbon emissions although it leads to an increase in demand for renewable energy generators. Appropriate planning of hydrogen storage can reduce the overall investment cost and promote a low carbon transition of the power system. Since hydrogen is a highly flammable fuel, to ensure safe operation and to timely detect a leakage, reliable safety sensors are applied. Indoor use of hydrogen detectors is recommended for indoor fueling operations. There are safety sensors on the market that can be used for the successful deployment of hydrogen technology. For hydrogen to take its rightful place in the energy transition, as with other energy technologies is sufficient development of the technology itself. Most hydrogen today is produced by steam reforming of natural gas, but green hydrogen can be manufactured by electrolysis using renewable electricity and use of renewable feedstock like biomethane.

14.1. Introduction

This energy transition faces challenges.as significant renewable energy must be installed and

integrated, while securing the supply and resilience of the power system is demanding[950]. Among potential renewable energies identified for the transition, hydrogen is a versatile, clean, and safe energy carrier that can be used as fuel for power generation or in industry as feedstock for production of various chemicals and products. Green hydrogen can be produced from renewable electricity and from carbon-abated fossil fuels. Hydrogen is emissions free at the point of use, can be stored and transported at high energy density in liquid or gaseous form for various applications including energy storage in fuel cells to generate heat and electricity or a transport fuel[950]. Hydrogen is among the most important low-carbon technologies more so with the introduction of carbon peaking and carbon neutral targets, and enforcement of policies that promote hydrogen energy technology[7]. The application of hydrogen is concentrated in four principal areas, namely: electricity, industry, transport and building heating, as well as use as a feed for industrial raw materials, energy storage and alternative fuels. The demand for hydrogen has been in a steady growth stimulating research into physical component and the integrated energy system with hydrogen. Physical components for hydrogen energy include electrolyzers, the hydrogen fuel cell, and the storage and transport carriers[7, 62].

14.2. Hydrogen Production

Hydrogen is produced from various carbohydrates, e.g. natural gases, coal, oil and oil products that are associated with CO₂ emissions although it can be derived from renewable power source, or biochemical processes and biomass. The global hydrogen demand is about 115 Mt/a in the form of 60% pure hydrogen, and 40% hydrogen mixed with other gases. About 75% of pure hydrogen is produced from natural gas (75%) and coal (23%), with electricity and oil accounting for the balance. Hydrogen derived from fossil resources is called grey, or blue, if carbon capture technologies while hydrogen from nuclear power is pink hydrogen. Green hydrogen produced from renewable energy sources [3, 6].. The global production of hydrogen is currently dominated by fossil fuels, with the most significant contemporary technologies being the steam reforming of hydrocarbons like coal and natural gas, while electrolysis of water, an energy demanding process is the greener option. [277]. The various methods for hydrogen production are discussed in this section.

14.2.1.Steam Methane Reforming

Hydrogen can be produced steam methane reforming (with and without carbon capture and storage (CCS),In this process, methane is used as a feedstock and as energy source for steam

generation. Methane and steam are first converted to syngas, which is rich in carbon monoxide and hydrogen and has some residual methane. The process occurs at 700–900 °C, and 20–40 bar. This is followed by a water-gas shifting (WGS) process in which carbon monoxide and steam form carbon dioxide and hydrogen. Carbon dioxide and residual methane are separated from hydrogen by downward pressure swing adsorption (PSA).

Reforming process leads to Synthesis gas (syngas) which is a mixture of hydrogen and carbon monoxide. H₂ and CO. Syngas is a raw material for production of many long chain hydrocarbons through fermentation, Fischer-Tropsch fuels and methanol to gasoline technology conversion. [934]

14.2.2.Dry reforming

In dry reforming, CO and H₂ are produced by reaction of methane (CH₄) and carbon dioxide (CO₂). However, the endothermic reaction minimizes reduction of CO₂ emissions, because the carbon dioxide (CO₂) emitted by fuel combustion generate the heat required for the reaction needs to be accounted for. Dry reforming also satisfies basic requirements of many processes in Fischer–Tropsch synthesis, as an efficient route for producing synthesis gas production yielding a H₂/CO ratio close to 1[444] .

The main limitation of Dry reforming compared with steam reforming is that it produces a lower syngas ratio (H₂/CO=1), The H₂/CO ratio is influenced by water gas shift reaction (WGS), which lowers the ratio because of reverse reaction which converts hydrogen to water. The H₂/CO ratio can be kept between 1 and 2 through partial oxidation of methane as shown in equation below through feeding water which promotes forward water gas shift reaction. The process also lowers process energy demand since partial oxidation is exothermic [934]. The temperature range for dry reforming process 700–1000°C[934].



Since the feed has got lower O/C and H/C ratios, dry reforming tends to form carbon deposition hence need to carry out the process at a higher temperature [934].

14.2.3.Steam Reforming and Water Shift Reaction

In steam reforming methane is combined with water vapor to produce CO and H₂ in the presence of a catalyst, in a reaction that is endothermic process at a temperature between 650 and 900 °C, to produce hydrogen yield of 60–70%[444].. The chemical reaction is demonstrated by a two-step reaction demonstrated below.



The process of steam reforming is often followed by a water shift reaction to improve hydrogen generation[28, 34, 62].

14.2.4. Partial Oxidation Reforming (POR)

The partial oxidation reforming is used to generate hydrogen at reduced energy cost since the process is moderately exothermic as opposed to steam reforming which is highly endothermic. In partial oxidation reforming, methane oxidized partially to H_2 and CO at atmospheric pressure and temperature of 700 and 900 °C. Complete conversion yields H_2/CO ratio of about 2 and reduced soot formation. A decrease in CO selectivity makes methane to react with oxygen to form carbon dioxide (CO_2) hence complete combustion which is strongly exothermic leading to formation of hot-spots in the reactor bed and coke deposition on the catalyst[444]. This process involves oxidation of methane to syngas



Partial oxidation reforming (POR) is an exothermic reaction. The reduce on energy consumption, the process can be combined with either dry reforming or stream reforming which are endothermic.

14.2.5. Autothermal Reforming (ATR)

Internal heating of a reactor is more efficient than external heating, and exothermal process is more economical. The partial oxidation reaction of methane as in POR is exothermic but the product has lower H_2/CO compared too endothermic steam reforming[444]. Autothermal Reforming combines the two processes i.e., POR and SR and occurs in presence of carbon dioxide. In ATR, a thermal zone exists in the reactor in where partial oxidation takes place to produce heat needed for steam reforming in the catalytic zone. The process is efficient as it requires no external heating while at the same time it is attractive because of the speed of the reactor stop and restart. The process also has higher yield of hydrogen and consumes less oxygen compared to partial oxidation reaction. The process also reduces formation of hot-spots hence no need to deactivate the catalyst[444].

14.2.6. Gas Switching Reforming

This is an alternative to SMR which is a novel process, cost effective intrinsic CO₂ capturing process. In gas switching reforming air and fuel (methane and water) enter a single reactor alternately where an oxygen carrier material which also acts a catalyst is oxidized or reduced, respectively. The oxidation stage involves the oxygen carrier being heated by the exothermic reaction, and the heat is utilized in reduction stage, the heat is utilized for methane reforming, to produce hydrogen and CO₂. GSR can be combined with combined cycle hydrogen turbines for to directly utilize hydrogen in the power generation, while excess hydrogen could be stored or supplied to a dedicated hydrogen system[3, 6].

14.2.7. Electrolysis

Hydrogen derived from renewable sources plays a marginal role with global production of less than 0.4 Mt/a, although there is significant potential for large-scale hydrogen production from renewable power is envisaged. Electrolysis makes use of electricity to split water into hydrogen and oxygen. Electrolyser technologies applied include alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), and solid oxide electrolysis cells (SOEC). Of the three technologies, with the alkaline electrolysis (AEL), being the most mature technology have industrial scale efficiency of about 65% on the basis of lower heating value. The process is however limited by limited startup and ramp-up dynamics which are reflected by the lack of application. The PEMEL technology is approaching market maturity, and a 6 GW PEMEL plant was commissioned for operation in Linz, Austria. Such plants produce up to 1200 m³ hydrogen per hour, with the ability to ramp and start up within seconds, enabling them to provide grid services. They operational flexibility of PEMEL has the potential to produce hydrogen at the lowest cost in the future. The solid oxide electrolysis cells (SOEC) are still under development at demonstration stage. They operate at high temperatures of (700–1000 °C) leading to start-up times and a relatively short useful life of 8000–20000 h). It is the overall hydrogen demand and policy measures that influence the hydrogen production technologies selected [1, 6].

14.2.8. Hydrogen Production Using Nuclear Energy

A potentially efficient method for hydrogen production may be attained by raising the water temperature before splitting its molecules in electrolysis or thermochemistry at a temperature range of 700°C to 1000°C. Since the current LWRs and near-term, water-cooled ALWRs produce temperatures below 350°C, they cannot be used for this process. However, coolants

for Generation IV reactors concepts can attain higher than 700°C and can be coupled to thermochemical plants. The use of nuclear reactors to supply the heat needed in the steam methane reforming (SMR) process is potentially more economical than water splitting. Nuclear-assisted SMR would minimize the use of natural gas in the process as and minimize the CO₂ emissions. [277].

14.2.9.High-Temperature Electrolysis of Steam

In this process, increased demand for thermal energy is offset reduction in the electrical energy demand, thus improving overall thermal-to-hydrogen heat conversion efficiency. Higher temperatures lower cathodic and anodic over voltages making high-temperature electrolysis of steam (HTES) advantageous from both thermodynamic and kinetic standpoints. The HTES overall efficiency appears less sensitive to temperature than the thermochemical processes[277].

14.2.10. Thermochemical Reactions

Of the several hundred possible reactions, two identified candidate thermochemical cycles for hydrogen production from water (i.e., cycles that enable chemical reactions to take place at high temperatures) with high potential for efficiency and practical applicability to nuclear heat sources are the sulfur-iodine (S-I) and calcium-bromine-iron (Ca-Br) cycles. Additionally, Argonne National Laboratory (ANL) identified the copper-chlorine (Cu-Cl) thermochemical cycle as another option which is a hybrid sulfur-based process that does not require iodine but has a single electrochemical process. However, nuclear power reactors emit trace amounts of radionuclides, chiefly noble gases which cause small doses of radiation to persons offsite, the total annual risk of which is less than one part in 1 million.

14.3. Cost of Hydrogen Production

Steam reforming remains the most widely used and cheapest hydrogen production method accounting for close to half of global production. The price for hydrogen is about 7 USD/GJ. The partial oxidation of hydrogen also provides a comparable price for hydrogen, but the capture of , greenhouse gases generated by thermochemical processes leading to price increase by 25–30% [277]. The main component of the cost of hydrogen is the cost of fuel or electricity used to produce the hydrogen. Cost evaluation shows that hydrogen from all reforming and gasification equipped with and without carbon capture is cheaper than renewable hydrogen. Solid fuel/coal gasification with capture will remain cost competitive in

the current and in anticipated net-zero emissions scenarios.[277]. Figure 14-1 shows the levelized cost of different types of hydrogen produced.

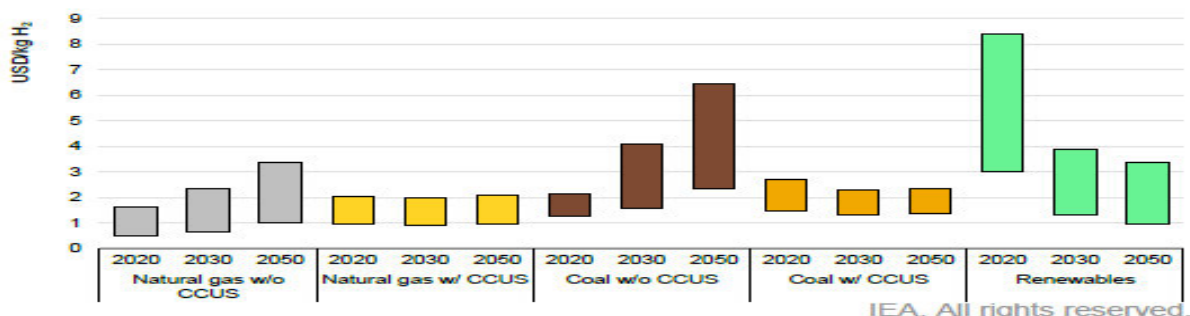


Figure 14-1: Levelized cost of hydrogen production by technology in 2020, and in the Net zero Emissions Scenario, 2030 and 2050 [277]

Figure 14-1 shows hydrogen production costs for the major methods of producing hydrogen, namely natural gas reforming (without and with carbon capture and storage [CCUS]), use of renewables, coal gasification (with and without CCUS). The costs are further compared to those costs associated with the net zero emissions scenarios for 2030 and 2050. It is shown that the cost of hydrogen produced from natural gas remains steady and most competitive. The cost of renewable hydrogen is currently high, but it is expected to drop by 2030, and further drop by 2050.

14.4. Feedstock for Hydrogen Production

Hydrogen is the most widespread chemical element on the earth and as molecular dihydrogen (H_2) can be obtained from several sources both renewable and non-renewable using different production processes. The significance of renewable hydrogen production has increased due to increase in the pure hydrogen demand, fossil fuels depletion, concerns over greenhouse gas emissions and global climate change. The availability of capital, desired hydrogen amount and purity hydrogen and the composition of available biogas will influence the selection of reforming processes[282].

14.4.1. Biogas

Biogas has significant potential for production of hydrogen through a variety reforming processes whose selection is guided by the composition of biogas, required purity of hydrogen, required volume, and process cost and availability of funding. The catalyst poisoning effect of hydrogen sulphide limits the use of biogas as a raw material for hydrogen

manufacture. By partially treating biogas to remove H_2S and 30–45% vol. carbon dioxide, the dry reforming process is appealing since it takes advantage of the of carbon dioxide to intrinsically act as oxidant in dry reforming. Use of biogas with CO_2/CH_4 ratio less than 1 requires alternative supply of oxidant to produce synthesis gas. Oxygen addition by DOR method is a potential route for hydrogen production from biogas, whose aim is to increasing the H_2/CO ratio[29, 932].

Through steam reforming, biogas can be used to manufacture green hydrogen, in a process where a catalyst refines and separates the hydrogen from the gas stream[34, 928]. The most common method used to manufacture hydrogen is by steam-reforming of natural gas, followed by pressure-swing adsorption to remove impurities. However, small reformers like those used for combined heat and power with biogas plants are in commercial operation[928]. Upon removal of carbon dioxide and water molecules, the methane (CH_4) left from biogas can be used for hydrogen synthesis and bio-fuel production. Methane can be split to hydrogen molecules (H_2) in a process that can be done in a steam/methane reformer. In the process, high pressure and temperature steam is combined with the methane (CH_4) to produces flow of hydrogen molecules and CO molecules[62, 929].

14.4.2.Biomethane

Biomethane may be used in form of Bio-CNG, is compressed biomethane having similar properties to with compressed natural gas (CNG) used as an alternative fuel for automotive application with better economy and lower emissions. The production of Bio-CNG requires the removal of impurities like water, nitrogen (N_2), oxygen (O_2), hydrogen sulphide (H_2S), ammonia (NH_3) and carbon dioxide (CO_2) from biogas for composition to be $>97\% \text{CH}_4$, $<2\% \text{O}_2$ at a pressure 20–25 MPa. Bio-CNG occupies less than 1% of its volume at standard atmospheric pressure and temperature[932, 933].

Biomethane has a significant application in fuel cell technologies for application are used for applications like power generation whereby fuel cells use hydrogen for power generation just like batteries. Other applications are Hydrogen-powered FCEVs which is environmentally attractive since they have no tailpipe emissions which makes them extremely clean as transport option to fossil fuel powered vehicles [282].Fuel cell technology in power generation is emission free and hence attractive [930].Biomethane is a source of renewable hydrogen, making hydrogen a green energy resource[28, 62]. Biomethane can be used as a substitute for natural making the process renewable. Therefore, it is technically feasible to

develop an integrated system which produces grid electricity and hydrogen for further electricity production from fuel cells and process applications in manner that yields negative greenhouse gas emissions. These promises to be a power pathway in the global transition to sustainable energy and electricity as well as sustainable development[282].

14.4.3.Natural Gas

Hydrogen is produced by natural gas reforming/Gasification which produces synthesis gas, a mixture of hydrogen, carbon monoxide, and a small amount of carbon dioxide through reacting natural gas with high-temperature steam. The carbon monoxide in syngas is reacted with water to produce additional hydrogen in this process[62]. The production of hydrogen by steam-reforming of natural gas is an established low-cost option for hydrogen production[951].

14.4.4.Coal

Coal gasification is used to produce hydrogen from coal, in a process that uses steam and oxygen to break molecular bonds in coal and form a gaseous mixture of hydrogen and carbon monoxide. It is easier to remove carbon dioxide and pollutants from gas obtained from coal gasification compared to coal combustion. In another method, low-temperature and high-temperature coal carbonization is applied. The coke gas made from pyrolysis (oxygen free heating) of coal consists of about 60% hydrogen, while the rest is methane, carbon monoxide, carbon dioxide, ammonia, molecular nitrogen, and hydrogen sulphide (H₂S). Hydrogen can then be separated from other components of coke gas using the pressure-swing adsorption process. [141, 278, 951].

14.4.5.Petroleum Coke

Petroleum coke can be converted to syngas which is rich in hydrogen through coal gasification. Other constituents are hydrogen, carbon monoxide and H₂S from the sulphur in the coke feed. Gasification process is used to produce hydrogen from almost any carbon source[951].

14.4.6.Depleted oil wells

Hydrogen can be extracted by injecting appropriate microbes into depleted oil wells to allow them to extract at low production costs are low. Concentrated CO₂ is produced by this method that could in principle be captured[951].

14.4.7. Water

The electrolysis of water splits water into hydrogen and oxygen and contributed a meagre 0.1% of hydrogen production in 2020. The process of hydrogen production by electrolysis is 70–80% efficient i.e. the conversion loss is 20–30% compared to steam reforming of natural gas whose thermal efficiency is 70 to 85%. The electrical efficiency of electrolysis is projected to reach 82–86% by 2030, as progress in this area continues. The temperature at which water electrolysis occurs is 50–80 °C (120–180 °F), while steam methane reforming requires takes place at 700–1,100 °C (1,300–2,000 °F). The main difference between electrolysis and methane reforming is the primary energy i.e. electricity for electrolysis and natural gas for steam methane reforming[951]..

Electrolytic cells are of their main types, solid oxide electrolyze cells (SOECs), polymer electrolyte membrane cells (PEM) and alkaline electrolysis cells (AECs)., with alkaline electrolyzers being traditionally are cheaper in terms of investment, but are less efficient.. They make use of nickel catalysts. The PEM electrolyzers, are more expensive since they use more expensive platinum group metal catalysts but are more efficient and can operate at higher current densities. Large scale hydrogen production can make them more economical and cheaper on basis of economies of scale and higher efficiency [951].

14.5. Application of Hydrogen Fuel

Hydrogen (H₂) is predominantly used in the chemical industry for production of ammonia and methanol, with significant potential applications in industry, transportation, and power generation. Hydrogen is expected to become a significant fuel for the energy transition. Hydrogen has many applications like conversion of heavy petroleum fractions into lighter ones through hydrocracking, aromatization process, hydrodesulfurization and the production of ammonia via the Haber process which is the primary industrial method for the production of synthetic nitrogen fertilizer widely used in agriculture. Hydrogen is also used as a fuel in fuel cells power generation and potentially as a transportation fuel.

14.5.1. Industrial Applications

Almost all hydrogen produced in the US is used by industry for refining petroleum, treating metals, producing fertilizer and other chemicals, and processing foods. The industry has safely used hydrogen for decades in the following applications: Common industrial applications of hydrogen include petroleum refining, glass purification, manufacture of semiconductors, aerospace applications, fertilizer production, Welding, annealing and heat-

treating metals, pharmaceuticals production, used as a coolant in power plant generators, and hydrogenation of unsaturated fatty acids in vegetable oil.

14.5.2.Application in Transportation

Hydrogen might become an energy carrier for transport applications by application of fuel cells[951].. Since diesel remains the most dominant energy resource used in transportation there is a need to shift to renewable and low carbon sources of energy, like hydrogen [341], since the transport sector is a significant contributor of emissions accounting for about 14% of the global anthropogenic greenhouse gas emissions[166].

The use of hydrogen in transportation can reduce emissions from engines which are widely used in transportation. The hydrogen fuel cells can provide an alternative to internal combustion (IC) engines due to the clean exhaust emissions, fuel renewability and higher efficiencies compared to conventional fossil fuel engines. Except for the challenge of waste heat removal, hydrogen fuel cell vehicles have a potential to gain widespread acceptance except for existing challenges like waste heat removal in mobile applications[931].

Since hydrogen has a relatively low energy density compared to other fossil fuels, conversion of hydrogen into alternative fuel products, e.g. synthetic natural gas (SNG) or ammonia, is an option being considered. These processes require CO₂ or nitrogen as feedstock e.g.CO₂ from coal-fired power plants can be fed to P2G facilities. Methanation is part of a hydrogen technology chain (TC) used to produce, store and utilize SNG in an OCGT. The process involves capture of carbon and feeding back to the methanation process. An option is to use CO₂ from the direct air capture process as feedstock for the methanation process. The efficiency of electrolysis and subsequent SNG or ammonia synthesis is generally between 45–50%. It seems feasible to establish a continental long-distance transport of hydrogen/natural gas blends or SNG via pipelines, followed by a dedicated hydrogen pipelines and liquefied hydrogen/SNG/ammonia transport could emerge. [931].

14.5.3.Application in Power Generation

Hydrogen is an ideal raw material for a sustainable energy transformation, but with the challenge being where and how to get hydrogen from renewable sources. Renewable hydrogen can be produced using renewable energy sources and usually produced via water electrolysis[928]. Continued Integration of an increasing share of intermittent power sources above 40% of the electricity mix creates a need for operational flexibility. Hydrogen offers valuable advantages as it avoids CO₂ and particles emission, and can sustain large scale

deployment almost everywhere, and can be made available everywhere. Hydrogen is used to improve the efficiency and flexibility of the energy system[950].

In electricity generation hydrogen can be utilized in fuel cells, e.g. proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), hydrogen-fired gas turbines (HGTs). Fuel cells technically reverse the electrolysis process from the reaction between hydrogen and oxygen (air) in a redox process. Power generation from hydrogen requires the state-of-the-art efficiencies of about 50–60%. The PEMFCs offer quick start-up and flexible operation, and so far, demonstration projects with 500 kW capacity have been achieved. The SOELs, and SOFCs fuel cells are limited in their start-up and ramping. These systems can also run on alternative fuels, like biogas and biomethane[386, 387].. The high operating temperatures of fuel cells can be exploited to produce hydrogen via steam and carbon dioxide reforming for efficient hydrogen fuel production Hydrogen gas turbines which are still evolving can run on 100% hydrogen and will provide benchmark costs for upgrading gas power plants 10, 25 or 100% hydrogen, respectively. The efficiencies of 60% for combined cycle hydrogen turbines (CCHTs) is expected compared with 35-40% for open cycle hydrogen turbines (OCHTs)[101, 299].

14.5.3.1. Electrolysis Can Convert Excess Electricity into Hydrogen During Times of Oversupply.

Hydrogen can be applied to provide back-up power during power supply deficits or can be used in other sectors like transport, industry or residential, hence it valorises excess electricity, with the potential of valorisation of otherwise curtailed renewable energy being huge e.g. in Germany alone, in a scenario with 90% renewables, curtailment of more than 170 TWh/year is projected for 2050, which is equivalent to about half the energy needed to fuel the German passenger car fleet with hydrogen. Valorisation will thus create an opportunity for about 60 GW of electrolysis capacity for economical operation. This will depend on grid improvement in grid interconnectivity. Hydrogen serves as a source of centralized or decentralized primary or backup power. Power from hydrogen (or one of its compounds) can be switched on and off quickly just like gas which helps deal with sudden drops in renewable energy supply. In addition, electrolyzers may provide ancillary services to the grid, such as frequency regulation. Hydrogen is also used in specific fuel cell CHPs in industry and buildings thus provides a link between heat and power generation. [950].

14.5.3.2. Long-Term Carbon Seasonal Storage Medium

Hydrogen can be used in long-term, carbon-free seasonal storage unlike batteries, super-capacitors, and compressed air which can support balancing, but they lack either the power capacity or the storage timespan needed to deal with seasonal imbalances. Although the pumped hydro provides an alternative to hydrogen for large-scale, long-term energy storage; accounting for 95% of global power storage (162 GW worldwide), the remaining untapped potential is affected by local geographic conditions and is limited to about 1% of annual global energy demand (0.3 EJ) which is not enough to deal with seasonal demand difference e.g. Germany energy has about 30% higher demand in winter than in summer, while renewable generation is typically 50% lower in winter than in summer. In such a case, hydrogen remains a novel way to store energy with more and more large, hydrogen- based storage projects being planned, announced, or launched globally in countries like Denmark, Canada, Japan, and the Asia-Pacific region. The underground storage of large volumes of hydrogen is an -established practice with limited technological barriers. The cost of cost of hydrogen storage is projected reduce from €140/MWh (power to power) in 2030 for hydrogen stored in salt caverns compared to projected cost for pumped hydro storage of €400/ MWh in 2030..Hydrogen enable a more economical integration of large amounts of intermittent energy sources in the system and develop the much needed power system flexibility to maintain the resilience of the system[950].

14.5.3.3. Serve as Feedstock Using Captured Carbon.

Hydrogen-based chemistry can be used as a carbon sink and complement or decarbonize parts of the petrochemical value chain. Crude oil is today used as feedstock for manufacturing industrial chemicals, fuels, plastics, and pharmaceutical goods. Almost all these products contain both carbon and hydrogen. The application of carbon capture and utilization (CCU) technology as part of a circular economy or an alternative to carbon storage requires green hydrogen to convert the captured carbon into usable chemicals like methanol, methane, formic acid, or urea. This application of hydrogen would make CCU a viable alternative for other hard-to-decarbonize sectors like steel and cement production and would contribute to the decarbonization of part of the petrochemical value chain. The use of hydrogen and captured carbon for production of chemical feedstocks is still under research and development phase. Methanol production is, although local factors make it cost-competitive with an electricity price of EUR 30/MWh. In Germany, a combining carbon from steel production emissions with hydrogen from excess electricity to produce chemicals. [950]

14.5.3.4. Act as System Buffer to Increase Resilience.

Hydrogen can align global energy storage with changing energy demand, with its high energy density, long storage capacity, and variable uses making it suitable to serve as an energy buffer and strategic reserve. The energy system has a backup capacity of about 90 EJ (24% of final annual energy consumption and is almost exclusively held by fossil energy carriers. As electricity consumers switch to alternative energy carriers, application of fossil fuels as backup will reduce, since this buffer serves only applications that consume fossil fuels. The most efficient buffer should mix energy carriers that reflect end-use applications in include a mix of fossil fuels, biofuels/biomass/synthetic fuels, and hydrogen[950]

14.6. Handling and Transportation of Hydrogen

Hydrogen storage and transportation remain a challenge today, with storage currently done on a relatively small scale in tanks while large-scale storage envisioned include storage in caverns, Feasible storage facilities for hydrogen include are storage tanks, caverns, hydrogen trucks and hydrogen pipelines. These hydrogen storage systems can be assessed based on a state of charge concept like charging/discharging efficiencies, losses, hydrogen demand of compressor unit, and minimum storage reserve required. Hydrogen trucks are a special type of storage which also offers a means used for transportation. .[6]

14.6.1.Hydrogen Transportation

All these hydrogen technologies are still under studies and whichever hydrogen storage technologies will prevail on the pathway towards a hydrogen economy is still not clear. Important, decisive factors are establishment of hydrogen demand, the evolution of hydrogen production, the transport cost, price of feedstocks, etc. Therefore, any integrated power, natural gas, and hydrogen models for analysis should consider broad portfolio of hydrogen technologies and policy regulations which may influence the of hydrogen to be produced. .[6].

Since pipelines are by far the most deployed transport infrastructure resulting from technological maturity, high transport capacities, and cost competitiveness for distances below 2500 km, it is envisaged that by 2050, about one-third of renewable hydrogen will be internationally traded and via pipelines. It is further estimated that up to 69% of European natural gas transmission pipelines could be repurposed to transporting hydrogen fuel, or natural gas/hydrogen blends.[6]

Hydrogen pipelines can be classifying as high-pressure transmission or high/medium/low pressure distributions systems, but we currently have no unified standard for pressure levels. Both systems are linked through controllable pressure valves to ensure appropriate gas flow rates at the distribution level. Blending hydrogen and natural gas is envisaged in the transition, but current blending rates are just between 1% up to 10% by volume e.g., in Austria, blending of up to 10% of carbon-neutral hydrogen is allowed.

Compressor units (CUs) are also considered in integrated power and natural gas expansion planning literature. Compressors ensure adequate gas flow rates by compensating pressure drop along a hydrogen typically in an interval of 100–200 km. for gas transmission, multistage radial flow turbo-compressors with a compression ratio between 1.2 and 1.5 may be considered. The compressors may be powered by electric drives or gas turbines consuming part of the transported gas. As a rule, in general, compressor units are exclusively installed at transmission system level since pressure in the distribution system are often enough to meet natural gas demand. Since hydrogen has lower density than natural gas compressor units for hydrogen transportation are currently a crux, due to its lower density compared to natural gas. Modelling compressor units present challenges because the mathematical formulation is non-linear and non-convex.

Studies indicate that the existing natural gas infrastructure can contribute to the transition towards a hydrogen economy, particularly at the early stages when demand for hydrogen is still relatively low such that making hydrogen dedicated transport systems pose an economic risk. Therefore, an integrated expansion planning should utilize the well-developed natural gas infrastructure while considering its technical and regulatory limitations, like maximum blend rates. Also to be considered is the broad technology portfolio for future transmission expansion[6]

14.6.2. Hydrogen Storage

Hydrogen requires storage at terminals like refueling stations, transport, and users like ships, trucks, and vehicles. High storage volumes limit the use of hydrogen in mobile applications like transportation because it reduces space for load services. High pressure increases volumetric density, which renders storage an important technology for the advancement of H₂-based solutions. Hydrogen storage requires high-pressure tanks (350–700 bar) and, as a liquid, cryogenic temperatures below – 252.8 °C (H₂ boiling point). The gas may be stored on

the surfaces of solids (by adsorption) or within solids (by absorption). Liquid H_2 (LH_2) is generally stored in double-wall, vacuum super-insulated tanks. (e.g., ammonia)[952]

The variations of hydrogen storage are developed based on operating time, and needs of users e.g. the metal hydrides, range from mature systems in specific designs, as applied in submarines where they were used for a long time, to experimentally obtained systems which have not yet entered the market. Metal hydride hydrogen storage systems and compression technologies are efficient in small-to-medium scale energy storage systems. The hydrogen demand influences size and type of hydrogen storage [953].

Figure 14-2 shows the various storage pathways for hydrogen.

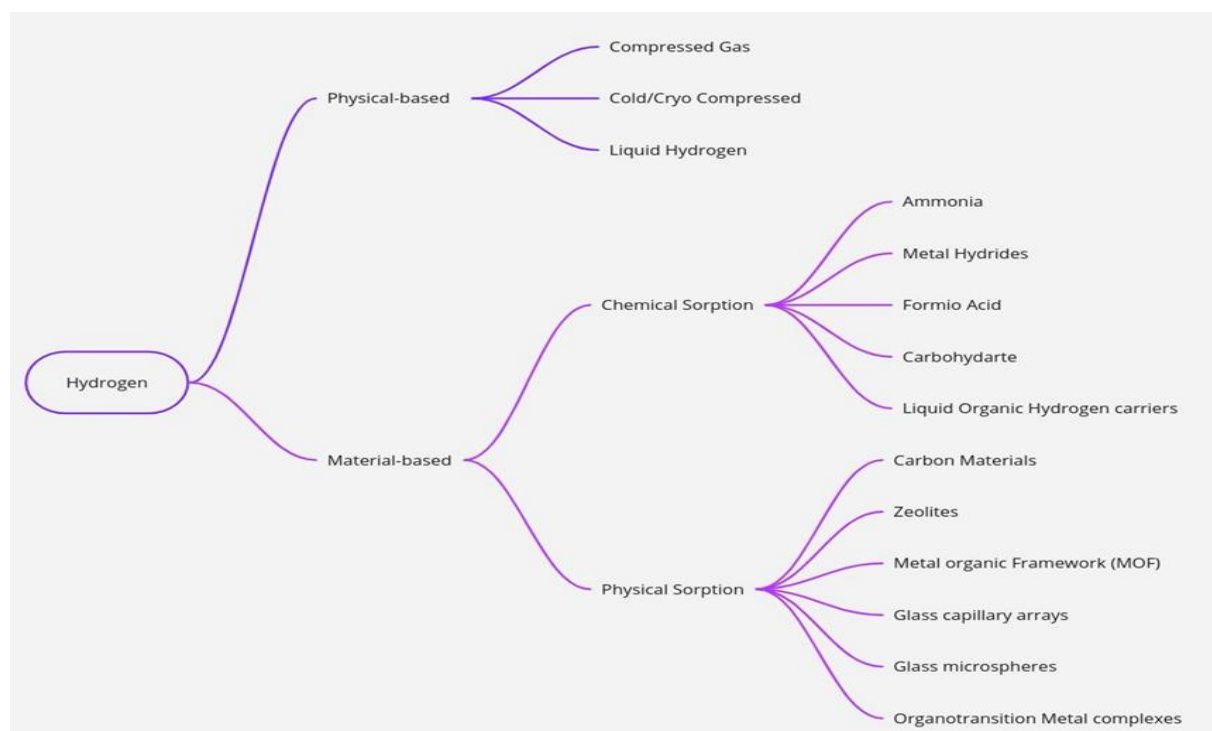


Figure 14-2: Hydrogen storage methods[953]

From

Figure 14-2 It is noted that hydrogen storage can be classified into physical i.e., liquid, compressed or cold/cryo compressed methods or on basis of material used i.e., chemical sorption or physical sorption. The compression technology is classified as mechanical and non-mechanical compression [953]

14.7. Planning and Modelling for Hydrogen Energy Future

Flexibility is a key requirement for highly renewable power systems. The Modelling energy storage systems and demand-side management requires a chronological (hourly) temporal framework which implies additional computational burden, that can be mitigated by reduction techniques, like representative periods or decomposition methods. Such a framework can mitigate short-term uncertainty when combined with ramping constraints, but modelling stochasticity is recommended to be an integral part of expansion planning[6].

Hydrogen and its variations technically extend the portfolio of energy carrier options making optimal sitting of power generation alongside hydrogen production and consumption units a complex undertaking as well as the choice of energy transmission technology. A state-of-the-art integrated power, natural gas, and hydrogen expansion planning models should be considered to facilitate decision making in network-based power and gas flows, e.g., via DC-OPF and steady-state gas flow equation which can be extended to include detailed line pack modelling to utilize pipeline storage capacity. There exists a knowledge gap in terms of beneficial effects of line pack on integrated expansion planning against its implied computational burden. Other gaps are in transmission of natural gas and hydrogen blends, blend rates, and constraints for the energetic properties of blends. There is also a policy constraint that should allow specifying the type/color of hydrogen to be produced (or not). There are limited holistic integrated expansion planning models that consider all the issues raised in terms of knowledge gap.[6].

14.8. Formulation of Gas Flow

At the center of integrated power and gas models is the formulation of gas flow where applied formulations include transport models, steady-state, or dynamic gas flows. The most basic modelling concept that can be adopted is a transport model that disregards physical laws for gas flows but only establishes lower and upper bounds. Its simplistic nature provides convenience, and minimal modelling and solution efforts particularly in in long-term models. The integer relaxation for truck scheduling and SMR unit commitment has benefits in terms of computational time with little impact on the overall optimal system cost. [6].

A comparison of physical characteristics of high-pressure gas flows, requires more sophisticated approaches starting with the Darcy-Weisbach equation where the steady-state flow equation for a horizontal pipeline is derived. This is a highly non-convex and non-linear formulation.

The friction factor, λ , (or f in American literature), which is a function of Reynolds number plays a key role for pipeline gas flows. The Reynolds number, Re , is generally based on average values, pipe roughness, ε , and internal diameter, D . The relationship of these parameters is represented in a Moody diagram, characterized by a zone for laminar flows ($Re < 2.320$) and one for turbulent flows ($Re > 2.320$). The Moody diagram differentiates between smooth, rough, and rough pipes. The friction factor is commonly described by the Colebrook-White equation. However, this implicit formulation requires iterative solution methods and thus, is not very practical for planning models. Gas system parameters, like pressure ranges, pipeline parameters, physical gas parameters etc., are often only vaguely/partially specified or not at all, making comparison of different approaches and case study results difficult. The range of application for the practical equations is subject to several limitations. To this end, we are applying the steady-state flow equation, and an explicit friction factor is recommended. The emergence of natural gas and hydrogen blends makes it more relevant to consider detailed gas parameters [6].

14.8.1. Challenges of Gas Flow Modelling Challenges

Power system expansion planning models are commonly formulated as linear programming or MILPs. Hence detailed modelling of pipeline gas flows needs linearization of the non-linear and non-convex steady-state gas flow. From a practical point of view, linear formulations do not require unconventional solvers[6].

14.9. Considering Linepack

The main difference between power transmission lines and pipelines is the storage capacity referred to as line pack which plays an important role in gas grid operation by offering operational flexibility in terms of balancing demand fluctuations. Injection of hydrogen at the transmission level will increase the importance of linepack. [6]. The linepack can be quantified as the volumetric amount of gas that is stored in a pipeline at a given point in time under certain pressure and temperature conditions[6]. Considering linepack necessitates reformulation since the relation between linepack and average pressure is based on non-quadratic pressure variables. [6]. Depending underlying temporal framework additional linepack constraints can be useful e.g., specifying initial linepack at time $k = 0$, which makes sense otherwise linepack behaves like additional demand, leading to an initial ‘charging’ of the pipeline, thus increasing the number of pipelines. In a chronological hourly structure, neglecting this is likely to only have minor effects on overall modelling results because

continuous gas demand results in linepack not falling below a minimum value. In the case of representative periods this is different as the effects of neglecting initial linepack increase not only with the number of pipelines but also with the number of representative periods [6].

In future, Linepack is likely to become even more relevant for integrated power, hydrogen, and natural gas systems. Linepack storage could provide additional flexibility, e.g. for large-scale hydrogen generation plants. Only a small fraction of integrated expansion planning models considers detailed linepack at the moment as it represents additional computational challenges. The modelling of linepack in case of natural gas/hydrogen blends, will require additional binary variables in order to ensure identical direction of natural gas and hydrogen flows, thus further increasing computational burden[6].

14.10. Sustainability of Hydrogen Energy

Hydrogen has also recently emerged as a clean fuel that is capable of operating thermal power plants. This creates room for future power plants to operate by blending natural gas with synthetic fuels including hydrogen. Hydrogen made through steam methane reforming (SMR) requires CCS technologies since CO₂ is produced during the process. The cost of producing hydrogen from natural gas ranges is between 0.5-1.7 USD/kg. However, using CCS technologies to reduce the CO₂ emissions adds to the cost of production by up to 1-2 USD/kg. Production of renewable hydrogen through electrolysis costs around 3-8 USD/kg which is higher but the cleanest method of producing hydrogen. The production cost of Hydrogen is expected to reduce globally as its adoption gathers momentum [252].

14.11. Cost and Carbon Emission

Investment in hydrogen equipment increases investment costs and O&M costs in the process of achieving the goal of carbon neutrality, through substitution of grey hydrogen in applications like industry, transport, heating and power generation. The carbon emission reduction from replacing grey hydrogen with green hydrogen is based on the assumption that 1 kg of hydrogen produced from coal produces 20 kg of CO₂ [7, 22, 23]

14.11.1. Levelized Cost of Hydrogen

A sustainable energy system needs green electricity and green molecules as well to shift from fossil to electrified chemical industry. A promising LCOE of H₂ is found in all importing scenarios with an average of 5.20 €/kgH₂. Transport of hydrogen via pipelines (0.14 €/kg/1000 km) is noted as optimal solution for the studied cases. Further investigation is required for importing renewable energy via other types of molecules and e-fuels such as

ammonia, methanol, and methane from the Middle East and North Africa (MENA) to the EU[39, 954].

14.12. Results and Discussion

Hydrogen has significant potential as a source of energy with applications in industry, transportation, power generation and heating. Replacing grey hydrogen with green hydrogen will significantly reduce a large amount of carbon dioxide in the hydrogen production process. The importance of hydrogen storage has emerged gradually as the share of renewable energy in the power system increases. Forecasts indicate a continued rise in the demand for hydrogen in the future. Planning for the future power structure with consideration of water electrolysis powered by renewable energy to hydrogen production could reduce a significant amount of carbon emissions. The low carbon energy transition cannot only consider the traditional electric load, but also the electric load from hydrogen demand in other sectors like the industry sector. Considering electrolysis for hydrogen production increases electrical load which increases demand for renewable energy sources, hence the need for more investment in renewable power capacity expansion like wind power and photovoltaics.

The main goal of the hydrogen energy transition, is to achieve a carbon-neutral hydrogen society, based on green hydrogen. Green hydrogen is produced via water electrolysis using renewable electricity. As the production and share of green hydrogen grows globally, green hydrogen is expected to be price competitive to the grey hydrogen production, which is produced from fossil fuels, within a decade. The cost parity can be achieved through increase in technical efficiency, equipment cost reduction and reduction in material prices, and manufacturing scaled up to achieve economies of scale which are currently in progress in several countries. The production of hydrogen via alkaline water electrolysis is a mature technology with commercially available megawatt (MW) scale installations, while production systems based on proton exchange membrane (PEM) and solid oxide (SO) electrolyzers are also at advanced stages of technology maturity [953]

Most hydrogen used today is produced by steam reforming of natural gas or from coal gasification. The growing demand for large volumes of low-emission hydrogen for the Net Zero emissions target creates new opportunities for nuclear power through many ways, including coupling nuclear reactors with electrolyzers while other methods that create hydrogen directly from nuclear power without electrolysis are under development. High-

temperature thermochemical hydrogen production, use heat directly derived from nuclear reactors to split water into hydrogen and oxygen at a system efficiency greater than 40%, which is higher than advanced electrolysis models whose efficiency limited to 30% [287].

The study showed that hydrogen-based vehicles can be used in marine, railways and aerospace industry and hence hydrogen-based fuel cell vehicles should be commercialized globally. Challenges facing hydrogen applications include the distribution and storage of hydrogen. Undeveloped hydrogen technologies have a high implementation cost for proper commercialization, which discourages vehicle manufacturers from adopting the technology [6]. Different countries should coordinate their energy requirements for the future to promote the use of hydrogen as a transition energy resource. Policy and regulatory measures and as well as funding for research and commercialization initiatives will pave the way for the take-off steps toward a hydrogen economy.

14.13. Challenges

There are various obstacles that should be overcome before the full benefit of hydrogen in the energy transition can be achieved. They include insufficient recognition of its importance for the energy transition, lack of mechanisms to mitigate and share the long-term risks of the initial large-scale investments, poor coordination across stakeholders, absence of fair economic treatment of a developing technology, and limited technology standardization and harmony to drive economies of scale [950].

Many hydrogen investments require a long period of 10 to 20 years particularly the early years and require infrastructure investments before the consumer demand can grow. The lack of clear and binding emission reduction targets or stimuli for specific sectors additionally discourages potential investors from long term risks. Applications immobility need a coordinated effort across industries to address the market mismatch between infrastructure deployment and hydrogen demand [950]

14.14. Social Aspects

As governments appreciate the potential and necessity of hydrogen technology development, more resources are invested in R&D, education, product manufacturing, etc. Society's willingness to support the hydrogen economy is quite important and must be taken into consideration. Likewise, projects should be clear about the ultimate motive in a carbon-neutral society, direct be accessible, and convince the populace enough to receive support.

How hydrogen implementation will affect people's lives is important and should leave a big effect on energy equality and social practices [953].

14.15. Safety

Hydrogen is an odorless, colorless, tasteless, and non-toxic gas that is 14 times lighter than air, having rapid diffusion (diffusion coefficient in NTP air is $0.61 \text{ cm}^2/\text{s}$) and buoyancy. The density of hydrogen is 0.08987 kg/m^3 at 0°C and 1 atm, making it necessary to store under high pressure. The gas is highly flammable with a lower flammability limit (LFL) of 4.1% and an upper flammability limit (UFL) of 74.8% in the air conditions of 25°C temperature and 1 atm. It has an explosion range between the lower and upper limit. The safety measures include gas detection systems and portable monitors equipped with alarms usually set at 20% and 40% LFL. The characteristics of hydrogen change when mixed with other gases based according to the volume percentage, thermodynamic properties, and ambient conditions e.g., a mixture of hydrogen/methane in 70/30 vol % in comparison to pure hydrogen has lower flame speed (142 cm/s) and detonation of the explosive mixture with air (20%), lower UFL, and slightly bigger LFL (34% and 4.5%, respectively). It also has a higher ignition temperature compared with pure hydrogen. A mixture of air and hydrogen has eight times greater maximum burning velocity from natural gas/air and propane/air mixture. [953].

The risks in hydrogen storage include H_2 embrittlement, and the worst-case incident scenario is LH_2 storage rupture when a boiling liquid expanding vapor explosion (BLEVE) is expected. BLEVE's hazards include a blast wave, fireball, and projectile. The safety challenges in storage on the consumer side (e.g., oil refiners) has traditionally favored its in situ production. A feasible option for hydrogen transport is by converting into a chemical carrier (e.g., ammonia)[952]. Leakage of a flammable or detonable mixture can lead to a fire or detonation. Gas leakage when ignited can lead to deflagration and detonation hazards, whose amplitude is a function of factors like amount of hydrogen released, the air conditions, space limitation, location, and strength of the ignition source. The risk of detonation or fire is low in open spaces, but higher in closed spaces.

To ensure safe operation and to timely detect a leakage, reliable safety sensors are applied. Indoor use of hydrogen detectors is recommended for indoor fueling operations. There are safety sensors on the market that can be used for the successful deployment of hydrogen technology. Integrated use of Failure Mode and Effect Analysis (FMEA), HAZard Operability Analysis (HAZOP), and Fault Tree Analysis (FTA) are strongly advised for

prevention of hazards. The use of FMEA reduces the possibility of deficiencies, identifying the areas that are more prone to failure occurring. FMEA on the other hand reduces them by application of appropriate corrective actions. HAZOP analysis is applied is used to analyze While HAZOP analysis applied in incident identification and potential scenarios, whereas FTA analysis is used to analyze the probability of their happening. Incorporation of well-established practices in future projects, and personnel training and education in hydrogen safety, are becoming standard in hydrogen safety engineering[953].

14.16. Strategies

The energy transition of any kind can't happen, and won't be achieved without implementing the political solution, developing national strategies and action plans with clear agenda, development methodology, adequate legislation, and financing. Many countries and political entities have put in place national plans for the integration of hydrogen into an energy transition, in the form of the upgrade by upgrading national energy plans with RES and clean energy production. Hydrogen use has spread out across the globe from most urban places to places with quality hydrogen development away from R&D centers, like is the case with Patagonia [953]

14.17. Conclusions

Hydrogen has emerged as a fuel for multiple applications like transport, power generation, and heat production. Hydrogen and fuel cell technologies have the potential to enable this transition to a clean, low-carbon energy system in a transformation that will result in significant reduction in greenhouse gas emissions and better air quality Hydrogen can store and move energy, enabling energy exportation but its application in the energy sector remains restricted. This creates obstacles to the wider application of hydrogen since renewable hydrogen can be produced by splitting water which is an energy-intensive process with most of electricity globally coming from fossil fuel and nonrenewable sources. Since currently energy needed to produce renewable hydrogen is more than the energy in hydrogen, hydrogen is more of an energy carrier rather than an energy source. Hydrogen is a renewable, emission-free fuel when created with renewable energy sources like solar and wind.

Since hydrogen is a highly flammable fuel, to ensure safe operation and to timely detect a leakage, reliable safety sensors are applied. Indoor use of hydrogen detectors is recommended for indoor fueling operations. There are safety sensors on the market that can be used for the successful deployment of hydrogen technology. The growth of hydrogen technology is

already at a satisfactory level for its complete involvement in the energy transition strategies with several ongoing R&D projects estimating a rapid increase in hydrogen usage. The hydrogen has grown significantly proving the significant potential of hydrogen technology with focus set solve legislation, market growth, preparing industries and economics for the growth of hydrogen-based systems, and promoting global interconnection and cooperation of various sectors and regions to integrate hydrogen energy.

For hydrogen to take its rightful place in the energy transition, as with other energy technologies is sufficient development of the technology itself. Years of R&D of hydrogen technology seem to finally pay off. Hydrogen technology can positively cope with concurrent technologies for most applications, and even offer undoubtedly better products and services, although cost parity has not been reached yet in all aspects. As the scale of product increases, production costs will become economically profitable. The main goal of the hydrogen energy transition, is to achieve a carbon-neutral hydrogen society, based on green hydrogen, . Green hydrogen is produced via water electrolysis using renewable electricity. As the production and s share of green hydrogen grows globally, hydrogen is expected to be price competitive to the grey hydrogen production, which is produced from fossil fuels. within a decade. The cost parity can be achieved through increase in technical efficiency, equipment cost reduction and reduction in material prices, and manufacturing scaled up to achieve economies of scale. which are currently in progress in several countries.

14.18. Recommendations

The following policy actions are recommended to enable hydrogen contribution to the energy transition:

- i.) Provide long-term and stable policy frameworks to enable transition in all sectors i.e., energy, transport, industry, and residential.
- ii.) Develop coordination and incentive policies that support deployment of hydrogen energy solutions and adequate private sector investments.
- iii.) Ensure strong coordination in the transport sector among governments, car manufacturers, infrastructure providers, and consumers
- iv.) Reform the energy sector in terms of feed-in tariffs, manage net of curtailment, seasonal balancing of capacity, remuneration and taxation, with due regard of benefits of hydrogen to the energy system.

- v.) Provide financial instruments to motivate private sector investment by mitigating risks through instruments like public guarantees for early movers.
- vi.) Harmonise industry standards across sectors and regions to enable hydrogen technologies and capitalize on cost reduction[950].

CHAPTER 15:

FUEL CELLS AND ROLE IN THE ENERGY TRANSITION

15. Overview

Fuel cells convert the chemical energy of in fuel mainly hydrogen efficiently to electricity without combustion with significant potential applications in transport and power generation as presented in publication [309]. The process has significantly low emissions with water as the main product of the reaction compared to conventional equipment/techniques that are associate with greenhouse gas emissions.

The three main parts of a fuel cell assembly are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit. Fuel cells development partially focuses on optimization of catalytic the layer Of the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available.

The theoretical efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually about 60%. which is still significantly greater than efficiency of combustion engines. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2 , O_2), hydrazine (N_2H_4 , O_2), carbon/coal (C, O_2) methane (CH_4 , O_2). Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO_2 emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the

efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cell's reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85%. Although fuel cells have significantly higher conversion efficiency compared to the internal combustion engines or and gas turbines across their output power range making them ideal for a variety of applications ranging from mobile phones to large-scale power generation, their largescale adoption is limited by high cost and lower reliability. The key to sustainability of fuel cells revolves around the production of hydrogen, the efficiency and capacity factor of fuel cells relative to other renewable sources of energy as well as the size of the installation.

15.1. Introduction

Fuel cells are electrochemical devices used for the continuous conversion part of the free energy change in a chemical reaction to electrical energy. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2 , O_2), hydrazine (N_2H_4 , O_2), carbon/coal (C, O_2) methane (CH_4 , O_2).

Fuel cell technology is clean, flexible, and already demonstrated that they can effectively be used in applications like space vehicles, portable devices, and vehicle. Hydrogen can be sustainably produced from renewable sources with null amounts of carbon dioxide. The power system using hydrogen from renewable resources and fuel cell operates like a closed system with no net loss to the environment since water consumed is converted to gases while the gases are converted back to water. Power produced is transferred to chemical energy in the gaseous state and the gases are converted back to electricity[955].

15.2. Hydrogen in Fuel Cell Systems

Energy is a key component in all industrial applications and with sustainability concerns, hydrogen has emerged as one of the most abundant energy carriers in the world. Additionally, hydrogen fuel is fully environmental friendly since its combustion is emission free[956]. Hydrogen energy is in line with zero-emission policy towards which makes it fundamentally attractive for transport and power generation. In addition to this, hydrogen is truly sustainable energy resource because of the zero-climate change effect, and it is a highly efficient, reliable, and noiseless source of power[956, 957]

Hydrogen can solve the pollution problems in power generation by producing emission free energy from renewable energy sources. A sustainability assessment of hydrogen fuel based on the various dimensions i.e. technical performance, environmental, renewability, social acceptability and possible applications in the energy transition has identified hydrogen as one of the best ever technical concept compared with other ongoing energy producing systems[206, 322, 326]. Keeping in mind the current environmental conditions, fuel cell technology is one of the most reliable future energy solutions. The fuel cell is simple in nature and works fundamentals of electrochemical reactions which converts chemical energy from fuel into electricity with byproducts being water and water vapors. Electricity production is done from simple reactions of hydrogen and oxygen. Hydrogen based fuel cells are truly found to be the viable option for the energy market with full potential to upgrade ongoing technologies[955].

Hydrogen is attractive because of ability to be produced from both renewable and non-renewable sources of energy i.e. hydro, wind, solar, biomass, geothermal and non-renewable sources like coal, natural gas, nuclear for application in high-efficiency power generation systems, like fuel cells, in vehicular transportation and distributed electricity generation. Fuel cells operate by converting the hydrogen gas or hydrogen in a hydrogen-rich fuel like biomethane and an oxidant usually pure oxygen or oxygen from air directly into electricity in an electrochemical process.[308].

Unlike coal, gas or oil, hydrogen is not a primary energy source, instead its role closely mirrors that of electricity as an 'energy carrier', produced using energy from other sources and transported for future use, where the chemical energy stored can be used in transportation and distributed heat and power generation in fuel cells, internal combustion engines or turbines, with cleaner emissions mainly as water and no CO₂ at point of use [308].

Hydrogen can be used as a storage medium for power produced from intermittent, renewable resources including solar, wind, wave and tidal power, thus offering a solution to one of the challenges of sustainable energy, i.e. intermittency and variability of renewable sources. Local production of hydrogen can introduce f renewable energy to the transport sector and provide large economic and energy security and benefits of an infrastructure based on distributed energy generation. Hydrogen energy storage capacity provides a the potent link between sustainable energy technologies and a sustainable energy economy, within a hydrogen economy'[308].

There are three major technological challenges that must be overcome for a transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy. They are.

- i.) The cost of efficient and sustainable hydrogen production and delivery should be reduced.
- ii.) The new generations of hydrogen storage systems for vehicular and stationary applications should be developed.
- iii.) The cost of the fuel cell and other hydrogen-based systems should reduce[308].

An integrated hydrogen energy system of the future should combine small and large fuel cells for industrial and domestic decentralised heat and electricity power generation with extended hydrogen supply networks that can also fuel conventional internal combustion or fuel cell vehicles[308].

15.3. Design and Operation of Fuel Cells

The fuel cell works like batteries except that it does not run down or need recharging, hence they generate electricity and heat continuously if there is supply of fuel. The device consists of two electrodes i.e. a negative electrode (or anode) and a positive electrode (or cathode) that are sandwiched around an electrolyte. Fuel cells require oxygen, but the main fuel is hydrogen whose action produces electricity with water as the main product. The first fuel cell was designed in 1842 by W.R. Grove who named it as a gaseous voltaic battery (Cleveland and Morris, 2014). The term “fuel cell” was then coined in 1889, by the chemists L. Mond and C. Langer. The actual breakthrough in fuel cell development was a result of the introduction of a sulphonated polystyrene (SP) ion-exchange membrane for use as an electrolyte by W. T. Grubb in 1955, and by platinum deposition onto the membrane by L. Niedrach in 1958. The sulphonated polystyrene (SP) was replaced in 1966 by Nafion ionomer which is still in use today.[958].

A membrane is sandwiched between two flow field plates in a single cell or between two bipolar plates in a PEMFC stack. A flow field plate (FFP) in a fuel cell is used to supply i.e. hydrogen, and oxidant (air, O₂) then removes water, and collects generated electrons. Roles of the FFP also include separation of gases between the half cells and neighboring cells in a stack; act as an electronic conducting medium between the cathode and anode; facilitate even distribution of reaction gases since it possesses a specific flow field design with channels; provides reinforcement, and enable water and heat management and control.[958]

15.3.1. Construction of Fuel Cells

Many types of fuel cells have emerged that are suitable for different energy applications at varying scales, the different fuel cells share the basic design of two electrodes (anode and cathode) that are separated by a solid or liquid electrolyte or a membrane. The fuel, usually hydrogen or hydrogen-rich fuel and air are supplied to the anode and cathode of the fuel cell, where electrochemical reactions occur often in presence of a catalysts. The ions created are transported between the electrodes using the electrolyte with excess electrons flowing via an external circuit to supply electricity [308]. Figure 15-1 shows the main elements of a fuel cell.

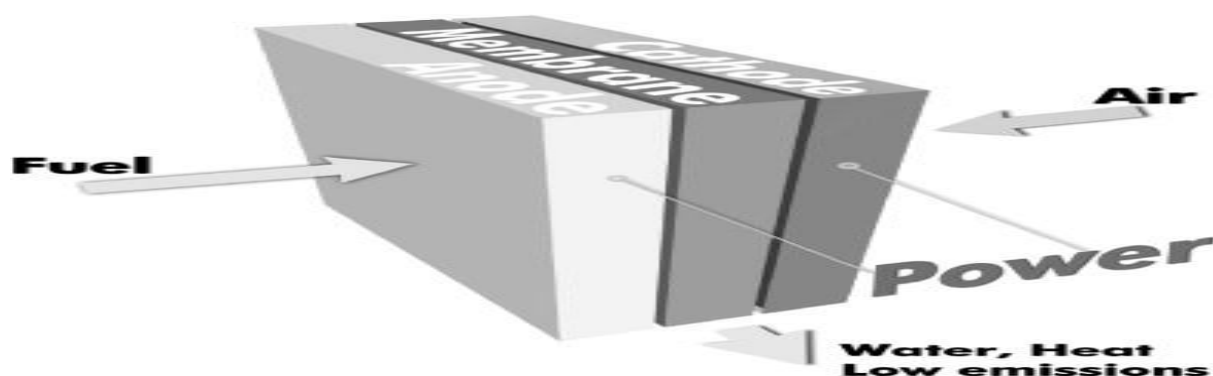
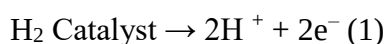


Figure 15-1: Schematic representation of a fuel cell

Figure 15-1 presents the general construction of fuel cells which consists of fuel supply, the anode, cathode, air or oxygen supply and the membrane. Water and heat are the main products of fuel cell reactions.

15.3.2. Working Principle:

Hydrogen gas is converted into hydrogen ions releasing free electrons at the negative electrode,



Under the influence of the catalyst in the electrode, the hydrogen ions react with the hydroxyl ions in the electrolyte to form water:



During operation, the free electrons from negative electrode flow through the external load towards the positive electrode. Negatively charged hydroxyl ions are formed when the electrons interact with oxygen and water in the electrolyte in a process shown below;



The hydrogen and hydroxyl ions formed then combine to form water as shown below:



A single hydrogen–oxygen cell generates electromagnetic force (emf) of about 1.23 V at atmospheric temperature of 298 K and pressure of 1 bar. Combining the cells in series, generates power ranging from few kilowatts (kW) to mega-watts. (MW).

15.4. Fuel Cell Concepts

Fuel cells convert chemical energy of in fuel efficiently to electricity without combustion, with low emissions compared to conventional equipment/techniques. It is therefore a fuel cell defined as an electrical chemical device that directly converts chemical energy to electricity. The three main parts of a fuel cell assembly are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit[443]. Fuel cells development partially focuses on optimization of catalytic the layer Of the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance [444]. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available. The theoretical thermodynamic efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60% [444].

15.5. Types of Fuel Cells

A fuel cell is said to be an electrochemical device used to convert the chemical energy in hydrogen or other fuel directly to electricity. Six common fuel cells are Polymer Electrolyte Membrane (PEM), Alkaline (AFC), Phosphoric Acid (PAFC), Solid Oxide (SOFC) and Molten Carbonate (MCFC)[959, 960].

15.5.1.PEM Fuel Cell (PEMFC)

The Proton Exchange Membrane fuel cells are equipped with a polymer electrolyte. And have efficiency range of 40-50%, The operate at a temperature of about 80°C. and therefore can be referred to as low temperature cells. Because of there are ideal for use in homes and vehicles. The fuel for proton exchange fuel cells needs to be purified while the catalyst used normally platinum increase cost. The PEM cells can generate sufficient power to supply commercial and residential customers at varying temperatures. The PEM fuel cell generator with Na metal and water chemical reaction can produce hydrogen with low emissions and noise. For applications in medium and high duty vehicular use. Advantages of PEM are low operating temperature, use of solid electrolyte, high power density, durability, and reliability proton exchange. The operating parameters of PEM fuel cells depend on operating conditions, with accurate estimation of performance efficient mathematical modelling. When used as source of mechanical power the PEM fuel cell is subjected to dynamic loading. The response voltage becomes lower than the steady-state conditions with voltage gradually increasing which leads to deterioration .PEM fuel cell operations [957]. The proton exchange membrane fuel cell (PEMFC) is demonstrated in Figure 15-2.

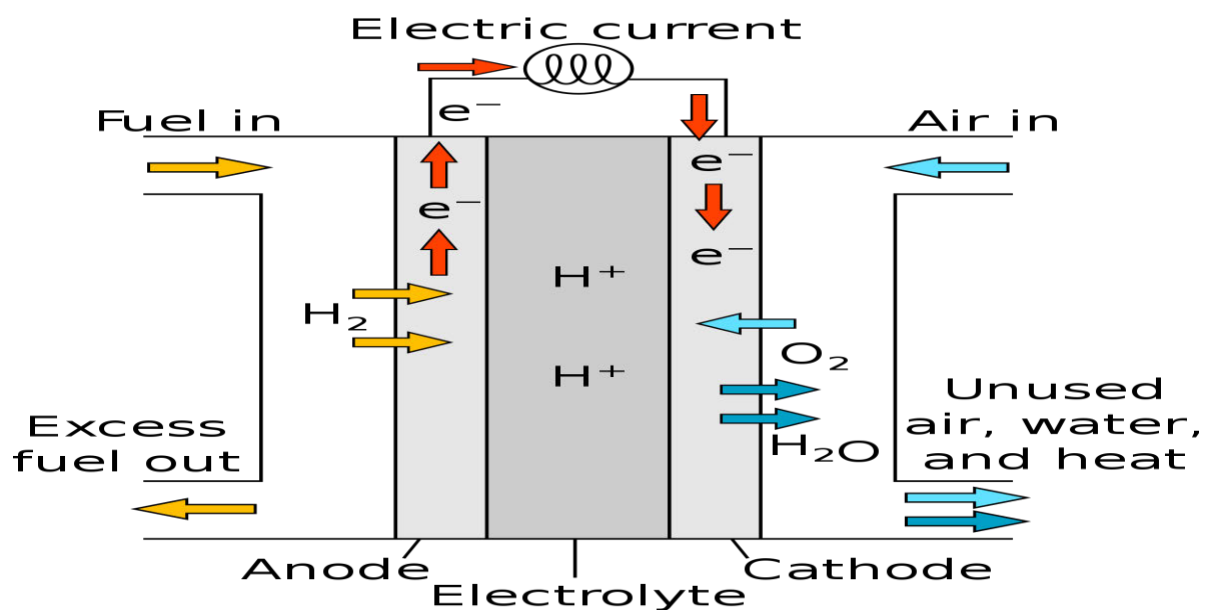


Figure 15-2: PEM fuel cell (PEMFC)[958]

From Figure 15-2, it is noted that hydrogen in the fuel cell is ionized to hydrogen ions which move through the electrolyte to the cathode where water is formed and discharged. Oxygen or air is supplied to the fuel cell through the cathode side. While fuel is supplied at the anode.

Electrons flow externally from the anode as electric current through load. In the proton exchange membrane fuel cell (PEMFC) the chemical energy in fuel is converted into electrical energy and water in a fuel cell where the heart is the Membrane Electrode Assembly (MEA) composed of a proton conducting polymeric membrane (PEM) which is sandwiched between the anode and cathode catalyst layers (CL) and gas diffusion layers (GDL)[958]

The applications of Proton Exchange fuel cells include power generation, transport and power for digital devices. They have a short life span caused by degradation while reusability of fuel cells limits its applications in the commercial sector. (Chakraborty et al., 2022). As a result of global concerns over greenhouse gases in the transport sector, many aviation companies are working on electrification of transport and use of fuel cells. It is at this point that the PEM fuel cells seem to be the most suitable option based on its operating parameters. (Hüseyin Turan et al., 2020).

15.5.2.Molten Oxide Fuel Cell (MOFC)

The molten oxide fuel cell (MOFC) is based on the oxygen-ion-conducting solid/molten oxide electrolyte also called liquid-channel-grain-boundary-structure (LGBS,) material that consists of TeO_2 solid grains and chemically compatible $\text{TeO}_2+\text{Te}_4\text{Bi}_2\text{O}_{11}$ liquid electrolyte located at the grain boundaries. The existing intergranular liquid channels facilitate the LGBS mechanical plasticity or ductility, that enable it to shape and alleviate problems caused by thermal incompatibility with electrodes (CTE), and high ionic conductivity. In the Molten oxide fuel cell (MOFC) the volume fraction of liquid varies between 0.15 and 0.17 at temperature range of 600–640 °C. Oxygen is supplied by air at the cathode. A single cell has power capacity 11.5 mW cm^{-2} at the current density of 90 mA cm^{-2} , at electrolyte thickness 2.5 mm, and temperature 640 °C[961].

The electrolyte in these fuel cells use salt components same as sodium or magnesium, and carbonates. Their efficiency varies between 60-80% and have a working temperature of about 600-700°C. So far molten oxide fuel cells with capacity of up to 2 (MW) have been developed. The main challenge is that the increase in temperature is limited as it leads to carbon monoxide (CO) poisoning which halts its operations[962]. Figure 15-3 shows the Molten oxide fuel cell (MOFC)

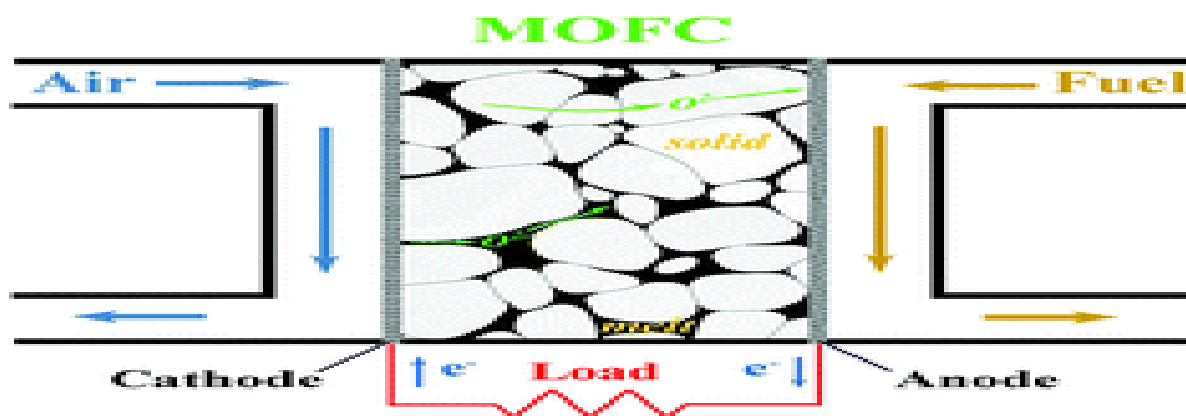


Figure 15-3: Molten oxide fuel cell (MOFC)[961]

Figure 15-3 shows a molten oxide fuel cell (MOFC) fuel cell with air flow at the cathode and fuel at the anode and solid oxide electrolyte at the centre.

15.5.3. Molten Carbonate Fuel Cell

The molten carbonate fuel cells (MCFC) make use of high-temperature compounds of salt e.g. sodium or magnesium carbonates as the electrolyte. They operate with efficiency ranges of 60 to 80% and operating temperature of 650 °C to 700 °C . The output capacity is between 2 MW must 100 MW. The advantage of the high temperature is that it limits the damage from carbon monoxide "poisoning" of the cell. Additionally, the waste heat can be applying to generate extra power in Rankine cycle plants or applied in thermal like process heating. The MCFC fuel cells use nickel electrode-catalysts which are cheaper than platinum electrodes used in other types of fuel cells. The challenge with high temperatures is that they limit materials used and applications off the MCFCs like homes –they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions. This Often requires the injection of carbon dioxide to compensate which adds costs.[959, 960]. Figure 15-4 shows the molten carbonate fuel cell.

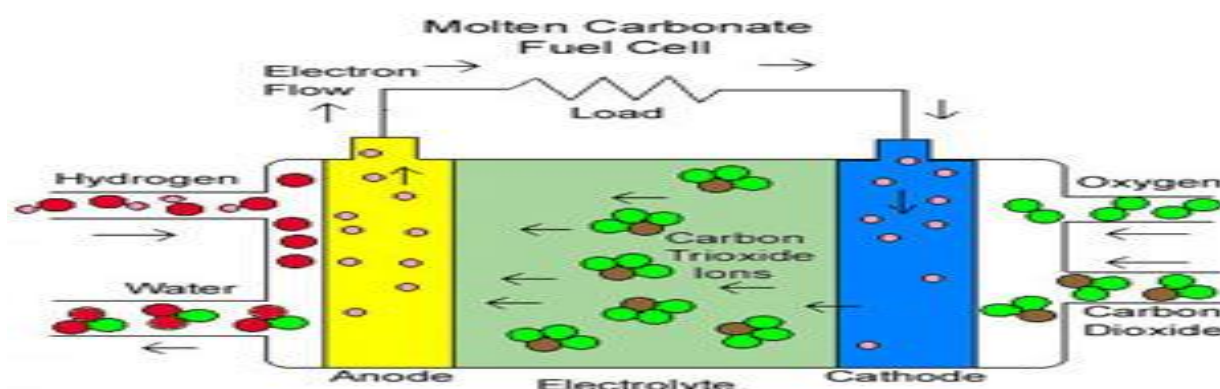


Figure 15-4: Molten carbonate fuel cell

Figure 15-4 shows the carbon trioxide fuel cell with carbon trioxide ions moving from the cathode to the anode and electrons flowing from the anode to the load as electric current. Hydrogen fuel is supplied to the anode side where water is also extracted from the fuel cell.

15.5.4.Solid Oxide Fuel Cell (SOFC)

The solid Oxide fuel cells use ceramic compound of metal like calcium or oxides as the cell electrolyte. They operate with efficiency of about 60 percent, and operating temperatures of 1000°C[82]. Fuel cells are the cleanest energy conversion systems but are limited by high investment costs compared to other energy conversion systems like gas turbines and internal combustion engines. They also operate at high operating temperatures which further limit their applications especially in automotive and domestic applications except for the proton exchange membrane fuel cells. The fuel cells also have high conversion efficiencies compared to conventional thermal conversion systems making them more competitive and attractive for long term investments. The fuel cells have wide range of applications and markets. With main limitations being size or weight and temperature for domestic and automotive use[444, 959].

The solid oxide cells need a high operating temperature operating environment and are commonly used in large, stationary power plants. High operating temperatures for the solid oxide batteries create opportunities cogeneration applications including space heating, industrial thermal and power applications, or use of a steam turbine in Rankine cycles for more power generation. Solid oxide fuel cells, need inverters to change the direct current to alternating current, and can be availed in relatively small, modular units. The solid oxide fuel cells are particularly attractive for urban application due to their compact size and cleanliness e.g. in Tokyo, there is are 25 kw units in operation [959].

15.5.5.Alkali Fuel cell

The Alkali fuel cells use compressed hydrogen and oxygen as a fuel and oxidant while the electrolyte generally used is the solution of potassium hydroxide (chemically, KOH) in water. The alkali fuel cell operates at an efficiency of about 70 %, and temperature of operations is between 150 and 200 °C, (about 300 to 400 degrees F). The generation output is between 300 watts (W) to 5 kilowatts (kW). A typical application of the alkali fuel cells is in Apollo

spacecraft to supply both drinking water and electricity. The main limitation is that alkali fuel cells use pure hydrogen fuel, and a platinum electrode catalyst which are expensive are expensive[959, 960].. The alkali fuel cell is demonstrated in Figure 15-5.

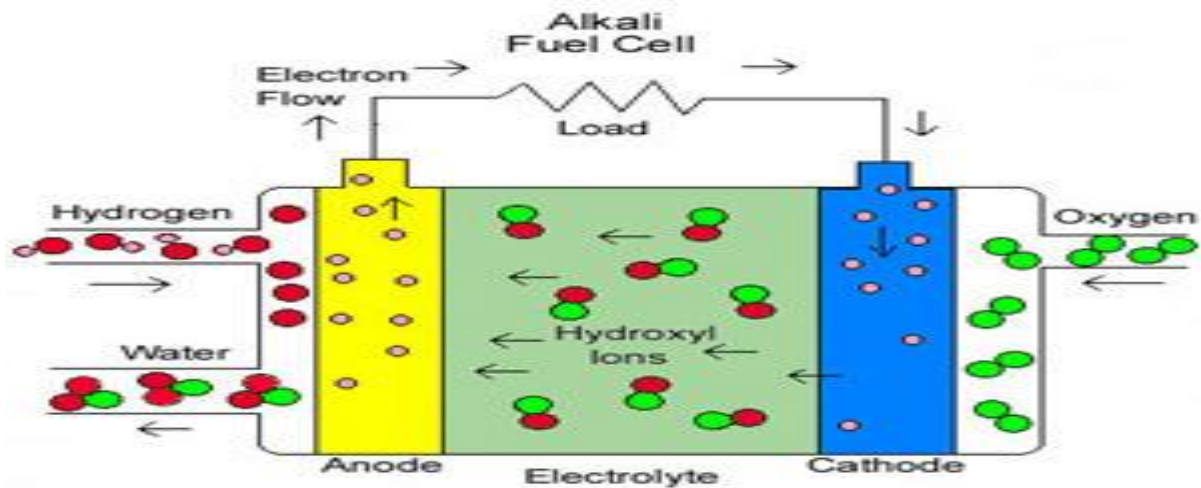


Figure 15-5: The alkali fuel cell

Figure 15-5 shows that in the alkali cell, oxygen is supplied through the cathode while hydroxyl ions migrate from the cathode to the anode where electrons flow as current to the external load. Hydrogen fuel is supplied to the anode where water which is the by-product of the process is extracted.

15.5.6. Phosphoric Fuel Cells

The Phosphoric Acid fuel cells (PAFC) use phosphoric acid as the electrolyte and have efficiency range of 50 to 80 percent, operating at a temperature range of 150 to 200 °C (about 300 to 400 degrees F). Operating phosphoric acid fuel cells have capacity range of 200 kW, and 11 MW. The advantage of PAFCs is that they can tolerate a carbon monoxide concentration 1.5%, making it possible to use a wide range of fuels. They use platinum electrode-catalysts and internal parts should withstand the corrosive acid[959, 960]. Figure 15-6 shows the phosphoric acid fuel cells.

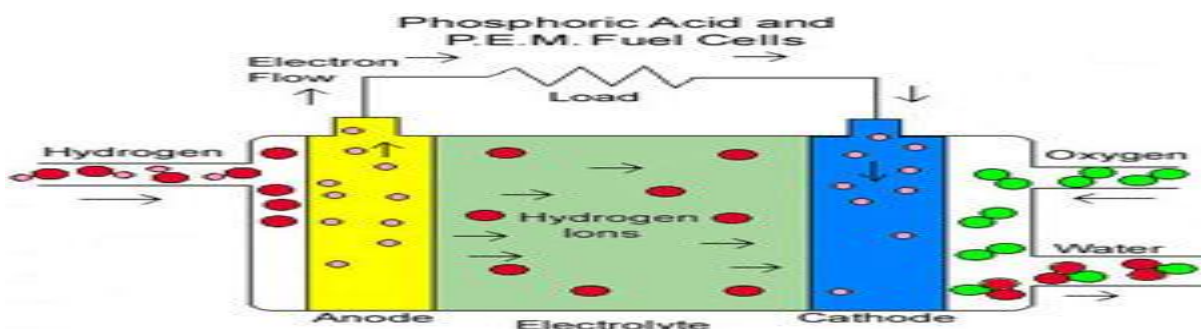


Figure 15-6: Phosphoric acid fuel cells

Figure 15-6 demonstrates the construction and operation of the phosphoric acid fuel cell which is also like the PEM fuel cell. In this fuel cell, hydrogen fuel is supplied to the cell through the node side. The hydrogen ions flow internally in electrolyte to the cathode where water is discharged from, and oxygen is fed to the cell.

15.6. Internal Reforming of Biogas in Fuel Cells

The technology to convert hydrogen to electrical energy is developed and close to commercialization, but parallel attempts for the direct use of biogas in fuel cells by internal reforming is also promising. This is feasible in high-temperature fuel cells like Solid oxide fuel cell (SOFC) and Molten oxide fuel cell (MOFC) because they have higher capacity to thermally integrate internal reforming and higher tolerance against contaminants while maintaining electrical efficiency close to 50% which is attractive [444]. The main limitation of internal reforming process for biogas is generation of carbon monoxide (CO)poison which poisons the fuel cell for concentrations of 50 ppm and higher. Other challenges of biogas reforming are variability of biogas quality and the poisoning of fuel cell catalysts by carbon deposition (coke) by CO disproportionation as well as the presence of sulphur traces [444]. Coke formation inhibits catalyst activity, blocks the pores leading to structural destruction destroy their structure. This carbon deposition can be reduced by addition of promoters like Sn, Li, Ru, Mo, Ca, Mg Sr, Ru, Ce, Rh, Pt and Pd at the anode [82, 444]. Sulphur causes a substantial decrease in the process of conversion to hydrogen because of strong sulphur chemisorption on the surface and within particles of the electrodic catalyst hence removal of sulphur is important. Poisoning is partially reversible but it limits conversion due to a slow desorption process[444]. Additionally, temperature gradients from endothermic reforming reactions causes destruction of the electrolyte an effect that can be reduced by addition of air to the biogas which prevents coke formation, and also removes the high temperature gradient due to exothermic reactions of methane[386, 387, 437, 444, 963].

Fuel cells using biogas offer a pathway to renewable and low carbon grid electricity generation[964]. Biogas can directly be converted electricity using fuel cells. The main challenge with biogas fuel cells is that they need a very clean gas and the system quite expensive. And is currently still at research and development stage [471]. Through steam reforming of biogas, "green" hydrogen can be produced which hydrogen with oxygen from air to produce electricity water vapor and heat. Fuel cells have wide application in

cogeneration systems for use in hospitals, learning institution, and remote telecommunication stations as a reliable source of energy. Other applications are transport and as emergency electricity supply systems[483].

In fuel cell generation, biogas is used to produce direct current electricity through electrochemical process. Fuel cells using biogas are cleaner than combustion as it produces less or no emissions at all [964]. Typical stationary biogas fuel cells are the high-temperature internal reforming systems like solid oxide fuel cells and molten carbonate fuel cells[965]. High internal temperatures in the fuel cells, reforms methane with steam to produce hydrogen which is used to generate electricity by reacting with oxygen. The state of California alone in the USA has more than 400 stationary fuel cells of which more than 11 are biogas fuel all producing about 180 MWe[966]. In a typical biogas fuel cell, synthesized biogas with about 65% methane + 35% carbon dioxide is reformed over a rhodium catalyst supported on a porous alumina-foam support. Reforming methods used include steam reforming and catalytic partial oxidation which use oxygen in air or pure oxygen for oxidation[967].

15.7. Sustainability of Fuel Cells

Sustainability is an important analysis for energy systems as well as manufactured systems. Sustainability consists of three basic dimensions: the Environmental, Economic and Social dimensions. Sustainability analysis for hydrogen as a fuel in fuel cells gives positive results in all three dimensions [1, 164, 956]. Benefits of fuel cell system and hydrogen can be defined using the thermodynamic principles especially the insights revealed by means of the exergy analysis. Development of hydrogen and fuel cell technology is an opportunity to sustainable development. The production and use of hydrogen production in fuel cells as a renewable energy provides an important solution environmental challenge [322, 955, 968]

15.7.1. Emissions Associated with Fuel Cell.

Biogas fuel cells generate extremely low atmospheric emissions with the only notable emissions being a result of oxidation or combustion of anode off-gas consisting of free hydrogen that has not reacted with oxygen(O_2), carbon monoxide (CO), and volatile organic compounds. The anode gas is usually processed by means of surface or catalytic burners which oxidize components and in the process little low nitrogen oxide emissions are emitted[1, 965].

Conventional fuels for vehicular applications produce pollutants that have adverse environmental effects, which has generated interest in environment-friendly vehicles for the present mobility sector. Hydrogen fuel-based vehicular technologies have gained significance because of the zero-emission policy targeting sustainable solutions. Compared to electric vehicles with a 200-mile range, fuel cell cars will be cheaper in the future. However, there is need to promote use of hydrogen as a passenger automobile fuel, by reducing the cost of fuel cell vehicle (FCV) to the level of an electric vehicle. Studies show that fuel cell vehicles, consume about 43% less energy than gasoline cars and produce 40% less CO making them more efficient and more environmentally friendly [957].

The emission factor for biogas fuel cells emissions is 0.09 kg CH₄/MWh while the carbon dioxide produced, the average GHG emission factor is 658.3 kg CO₂/MWh, and the while for N₂O (nitrous oxide), the emission factor is 0.001kg N₂O/MWh[965]. Based on these emission factors, the global warming potential over 100 years' time scale (GWP100) of the greenhouse gases i.e., the output-based greenhouse gas emissions in terms of CO₂ of methane for biogas fuel cells about 0.3 kg CO₂eq/MWh. The biogenic GHG of carbon dioxide is about 658.3 kg CO₂eq/MWh[965]. For nitrous oxide, the greenhouse gas emissions is about 0.26 kg CO₂eq/MWh [966]

15.8. Cost of Fuel Cells

The installation costs for biogas fuel cells range over \$8,000/kW for a fuel cell with a 250-300 kW capacity to about \$3,800/kW for a 6,140-kW fuel cell. This cost includes the cost of gas cleaning equipment, engineering, permits, and other direct costs[966]. The estimated Levelized cost estimated Levelized cost of biogas fuel cells energy is \$0.164 per kwh for a 200-kW fuel cell to \$0.079 per kwh for a 6,000-kW fuel cell.

High installation costs require state backed incentives to encourage the development of fuel cells. With 30% of the project or \$3,500/kW incentives, a payback period of less than five years can be realized. Through tri-generation of electricity, heat, and hydrogen from fuel cells, a feasible route to solving the hydrogen infrastructure problem facing fuel cell vehicle deployment. Can be achieved. [964].

Biogas is superior to natural gas as a fuel because its combustion is characterized by a high knock resistance and hence can accommodate higher compression ratios leading to more output and higher power density when used in internal combustion engines [471]. In some applications biogas is used as fuel for combustion engines, which convert it to mechanical

energy that rotates a generator to produce electricity. Theoretically, biogas can be used in all types of combustion engines, engines like gas turbines, diesel engines, and Stirling engines and others etc. [471, 474, 969].

15.9. Hydrogen Safety

Hydrogen safety also critical, encompassing technological, scientific, psychological, and societal issues. Hydrogen has an extraordinary safety record during many the many years of use. However, it is different other fuels due to its ability to migrate through tiny channels, while combustion properties are different from carbon-based fuels. This calls for diverse safety measures for those who interact directly with hydrogen and fuel cell technologies[308]. The main safety challenge with hydrogen fuel is that it can leak easily and ignite at relatively low temperature. Safe handling of hydrogen fuel just like other fuels depends on physical, chemical, and thermal properties and consideration of safe ways to accommodate those properties. If handled carefully, hydrogen is a safe fuel, even safer than conventional fuel currently in use. Unlike conventional fuels which produce hot ash, hydrogen combustion does not produce hot ash, Hydrogen in its pure form, burns with no hot ash and very little radiant heat. [955, 968].

15.10. Sustainability Measures for Fuel Cells

The key to increased or enhanced sustainability of fuel cells revolves around the production of hydrogen, the efficiency and capacity factor of fuel cells relative to other renewable sources of energy as well as the size of the installation. It is necessary to improve these factors for fuel cells to be competitive energy sources[970]. A fuel cell is an energy conversion devise or system that generates electricity from the chemical reaction producing water as the main byproduct, rendering the process very clean and renewable. The fuel cell economy and supply chain is strongly related to the country's economic aspect, like local and infrastructure costs, which makes it more relevant for implementation in developed countries[971]. Sustainability in fuel cells can be increased by.

- i.) The energy source pathway should be clean with low/no long-term carbon emissions., technology be applied to cut down emissions e.g. where carbon capture and sequestration (CCUS) is applied, the efficiency should exceed 90%
- ii.) Maximum efficiency of conversion from primary energy source to end use as electricity at point of use.

- iii.) There must be interdependence of fuel cell technology, energy use and primary energy source for sustainable outcomes and
- iv.) The materials used in construction and infrastructure assets should be sustainably sourced, and should have low energy demand, environmental impact and have established recycling pathways.

15.10.1. Results and Discussions

The main objective of chapter was to present fuel cells as a renewable source of energy for future sustainable energy needs as the global electricity demand continues to grow and the world races against time to cut down emissions from the energy sector and limit global climate change. There is a need to a wide variety of technologies for power generation and thermal applications which is the key driver in fuel cell research. Fuel cells are electrochemical devices that produce electricity from chemical energy through a chemical process between oxidizing and reducing agents. Fuel cell have emerged as top alternatives energy source for automotive and industrial applications. The, solid oxide fuel cell has shown the most potential device for high efficiency power generation above 100 KW as a result of pollution free reforming process [956].

A sustainable fuel cell and hydrogen energy industry will depend on cost reduction in hydrogen production methods, development of a large network of Hydrogen Refuelling Stations and further increase in fuel cell efficiency to lower cost of energy conversion. [956]. The main materials for improvement in fuel cell technology are the membranes, plates and electrolytes whose performance and costs and recyclability should be improved through research and development for cost competitiveness. Sustainability aspects of fuel cell technology should likewise address the efficiency of conversion, affordability, legal and policy framework, environmental impacts and social impacts and acceptance. [956].

Fuel cells mainly use hydrogen as a fuel for the electrochemical process which combines oxygen and hydrogen to directly produce electricity and water. Green hydrogen can be obtained by the reverse process of electrolysis, which oxygen and hydrogen using a renewable energy source like wind, wave, and solar energy. Clean hydrogen power is a uniquely clean energy source for heat and power generation since water is the only by-products. Therefore, use of fuel cells operating with hydrogen-rich or pure hydrogen fuel is a major factor in catalysing the transition to a future sustainable energy system.[308].

There is a global debates on hydrogen fuel cells and their advantages and disadvantages, which indicate that hydrogen is an environmentally-friendly alternative fuel to fossil fuels and can be applied in flexible and high-density power and propulsion in a wide range of industrial plant and transportation applications based on the hydrogen fuel cell technology[308]

15.10.2. Operating Temperatures

The main difference between the different fuel is the operating temperatures and type of electrodes used [956]. Figure 15-7 shows the operating temperature range for common fuel cells.

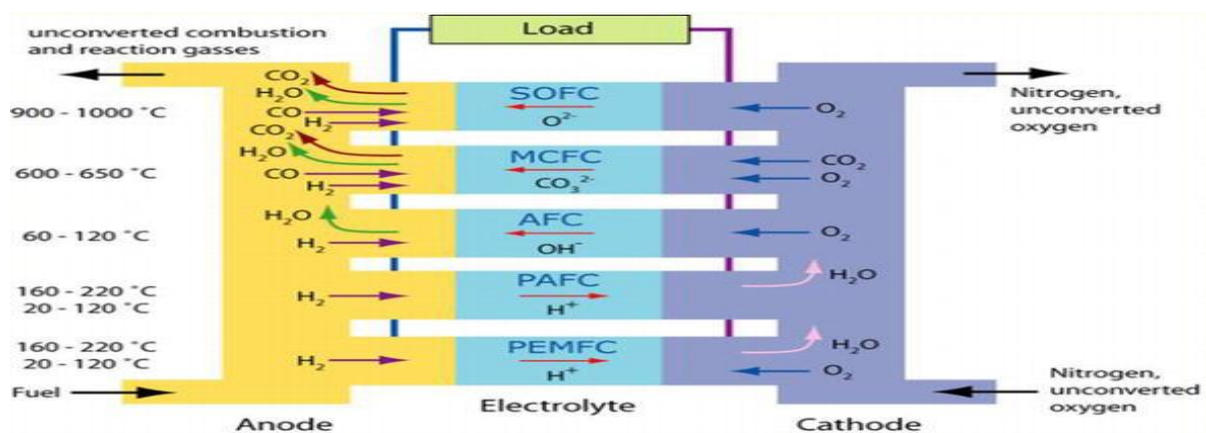


Figure 15-7: Fuel cells structures and operation temperatures[956]

From Figure 15-7, it is noted that the Solid Oxide (SOFC) has the highest operating temperature of 900 to 1000°C followed by the Molten Carbonate (MCFC) which operates between 600 and 650°C. Phosphoric Acid (PAFC) and Polymer Electrolyte Membrane (PEM) have lowest operating temperature of 20 to 220°C.

15.11. Applications of Fuel Cells

Fuel cells are alternative technology internal combustion engines in as prime movers for vehicles and stationary applications like distributed power generation. It is also projected that future demand for portable power generation supplies will exceed the capability of current battery technology[308]. This provides further market opportunities for fuel cells.

The transport sector has emerged as a leading user of fuel cell technology generally using the PEM type fuel cell as a preferred choice mainly due to the operation temperature. Many automotive manufactures for fuel cell vehicle i.e. Toyota, Hyundai, Honda, and Mercedes tend to use PEM whose efficiency is generally between 45–60% es[35, 93]. On the other

hand, not only automotive sector but also all fields of transportation industry, given importance on fuel cells. Figure 1 below illustrates products in the transport sector which includes land, marine and air vehicles and the general capacity of fuel cells used ranging from bicycles as the simplest to aeroplanes [956]. Figure 15-8 shows the various applications of fuel cells in the transport industry.



Figure 15-8: Fuel cells in transportation industry.

From Figure 15-8 , it is noted that fuel cells have potential use in all sectors of transport and vehicles ranging from bicycles, vehicles, buses, and aircrafts.

Fuel cells are classified based on the nature of their electrolyte, which influences the operating temperature, fuel type and the range of applications. Electrolytes used can be classified acid, base, salt, solid ceramic, or polymeric membrane and should have ability to conduct ions. Table 1 summarises the characteristics of various fuel cell types[308]. The various applications of fuel cells are summarised in Table 15-1.

Table 15-1: Fuel cells and their applications[959]

	Type of fuel cells	Applications
1	PEM type fuel cell	Used in transport sector has emerged as a leading user of fuel cell technology generally using the
2	The high-temperature solid oxide fuel cells (SOFCs)	Can be used in distributed generation
3	molten carbonate fuel cells (MCFCs)	Can be used distributed generation, Large-scale power generation
5	Solid oxide	Medium- to large-scale power and CHP, vehicle auxiliary power units, off-grid power and micro-CHP. The solid oxide cells need a high operating temperature

		operating environment and are commonly used in large, stationary power plants
6	Phosphoric acid	Medium- to large-scale power and CHP
7	Proton exchange membrane	Mobile, portable, low power generation
8	Alkaline fuel cell	Mobile, portable, low power generation
9	Direct methanol	Portable, mobile

From Table 15-1, it is noted that fuel cells are mainly used in transport sector, decent raised generation of power and heat (CHP) and charging applications. Fuel cells in power generation can be used in off grid and on grid applications.

15.12. Summary of Types of Fuel Cells and Applications

The various fuel cells available have different characteristics, features, and ideal applications. Fuel cell technologies have emerged as a good solution for clean and sustainable power supply by meeting the energy demand in a positive manner. Fuel cells are used for stationary applications like power generation and CHP and mobile like transport applications, portable power among others [972]. The fuel cells and applications are summarised in Table 15-2.

Table 15-2: Types of fuel cell, features and applications[959, 960]

Type of electrolyte	Operating temperature (°C)	Average (°C)	Applications	Electricity capacity range (kW)	Average kW	Electrical efficiency (%)	Average Efficiency (%)
Proton exchange membrane or Polymer electrolyte	60–110	85	Mobile, portable, low power generation	0.01–250	125	40–55	43

membrane (PEM)							
Alkaline	150 –200	175	Space, military, mobile	0.1–50	25	60–70	65
Direct methanol	60–120	90	Portable, mobile	0.001–100	50		
Phosphoric acid	175–210	192.5	Medium- to large-scale power and CHP	50–1000	525	40–45	43
Molten carbonate	600 –650	625	Large-scale power generation	200–100,000	50.100	60–80	70
Molten oxide fuel cell (MOFC)	600-700°C	650	Stationary medium to large-scale CHP	2,000	1000	60-80	70
Solid oxide	500–1000	750	Medium- to large-scale power and CHP, vehicle auxiliary power units, off-grid power, and micro-CHP	0.5–2000	1000	40–72	56

Global average	427	10,365	58

From Table 15-2, it is noted that the common types of fuel cells are the proton exchange membrane alkaline and direct methanol which have lowest temperatures of operation, phosphoric acid fuel cell, molten carbonate and solid oxide fuel cell which have higher operating temperature range.

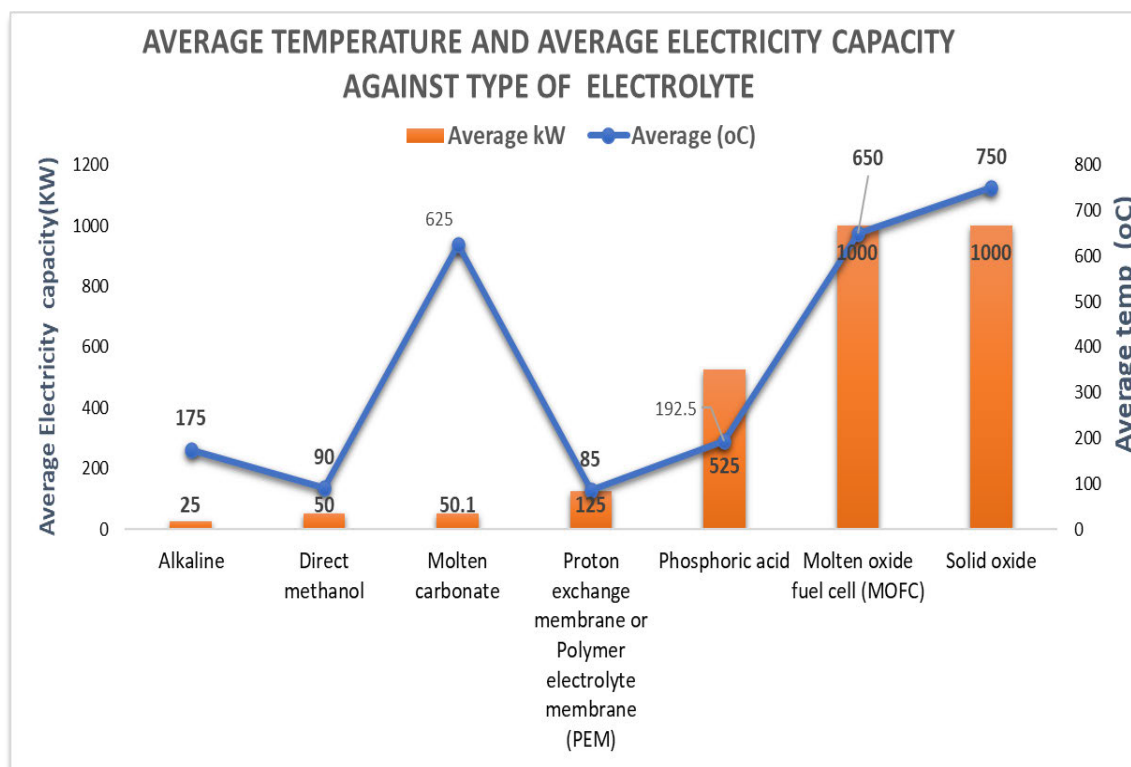


Figure 15-9: Average capacity and working temperature for different fuel cells.

It is noted from Figure 15-9 and Table 15-2 that the average operating temperature for fuel cells across all types is about 325°C, temperature, average capacity of 10.4 MW, and electrical efficiency of 51.4%

Fuel cells have significantly higher conversion efficiency compared to the internal combustion engines or and gas turbines across their output power range making fuel cells ideal for a variety of applications ranging from mobile phones to large-scale power generation. However, the main undoing for fuel cells in competing applications with thermal engines is their high cost and limited reliability[93, 308]. Figure 15-10 shows the average efficiency and capacity of the various fuel cells..

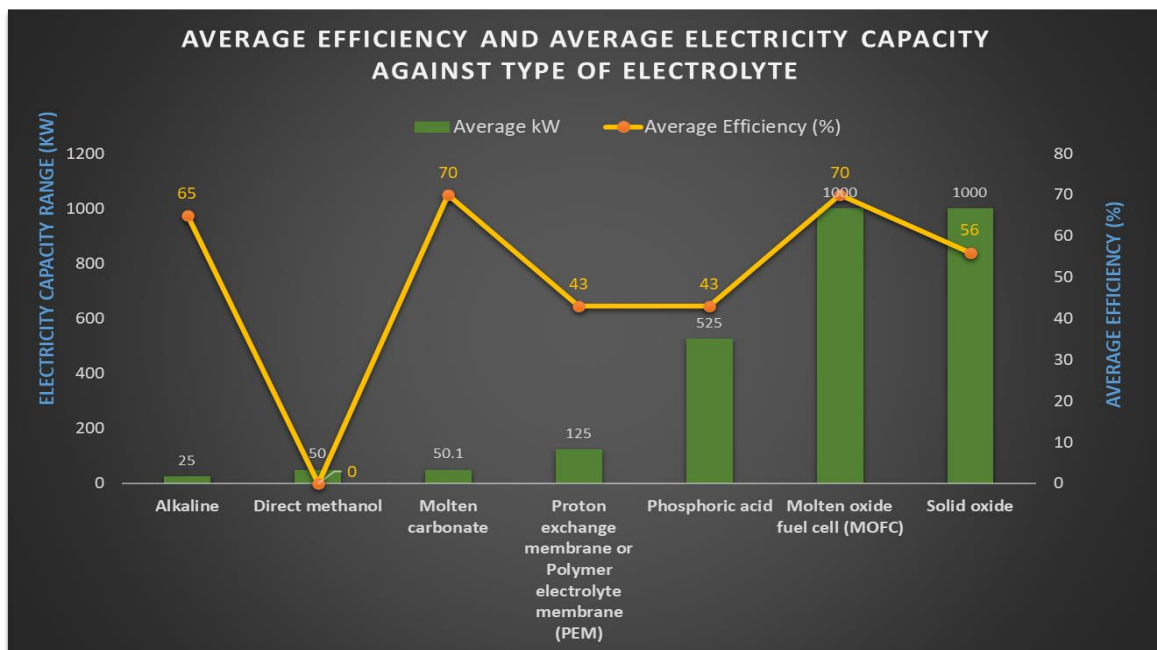


Figure 15-10: Average efficiency and electricity capacity of various fuel cells

The high-temperature solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) can be used in distributed generation that currently use natural gas, hence an opportunity to develop and use of this technology independently from the establishment of a hydrogen infrastructure which will provide a transition to the hydrogen economy, with significant efficiency gains the commercially available hydrocarbon fuels which can also effectively operate on renewable biofuels if they become cost-effective, and ultimately competitive with high efficiencies on hydrogen.[308, 326]. Fuels cells are also being developed as alternatives for auxiliary power units for vehicles and for off-grid power applications as replacement of small diesel generators. Fuel cells do not require an external reformer for conversion of a hydrogen-rich fuels like biomethane to hydrogen enabling them to work on a variety of fuels and eliminate cost incurred in external reforming. Therefore, fuel cells are particularly suitable for cogeneration applications because they produce high-grade waste heat alongside electricity. [308].

Although the Low-temperature proton exchange membrane fuel cells (PEMFCs) and alkaline fuel cells (AFCs) have higher power density than any other fuel cell systems, they are limited by the requirement for expensive platinum catalyst and require very clean or very pure hydrogen. The PEMFCs and AFCs were developed in the 1950s and used in the NASA space

programme. The proton exchange membrane fuel cells (PEMFCs) are favourites for mass-market applications in automotive and small-scale cogeneration applications, with ongoing global effort to develop commercial systems[308].

The Phosphoric acid fuel cells (PAFCs) have the advantage of more tolerant to impurities in hydrogen than the proton exchange membrane fuel cells (PEMFCs) or AFCs. The PAFCs are preferably used for stationary power generation and commercial vehicles like city buses. The Phosphoric acid fuel cells (PAFCs) are available commercially but are relatively expensive thus limiting the market uptake. The direct methanol fuel cells (DMFCs) use methanol and can be used in applications mobile phones and laptop computers[308].

15.13. Advantages of Fuel Cells

Hydrogen based fuel cell technology presents several advantages over other power sources, which are summarised in Table 15-3.

Table 15-3: Benefits /advantages of fuel cells [973].

	Benefit	description
1	Renewable and Readily Available	Hydrogen is the most abundant and renewable element globally in the universe even though its extraction, mainly from water is a challenge.
2	Hydrogen is a Clean and Flexible resource to support Zero-Carbon Energy Strategies	Hydrogen fuel cells are clean with no adverse environmental impact during operation the products are simply heat and water unlike. Land requirements for hydrogen is significantly smaller than biofuels or hydropower.
3	More Powerful and Energy Efficient than Fossil Fuels	The fuel cells provide high-density source of energy at higher energy efficiency. Hydrogen fuel has the highest energy content by weight compared to other fuels. Hydrogen at High pressure as a gas and liquid hydrogen contains about three times the gravimetric energy density i.e. about 20MJ/kg of diesel and LNG and has a similar

volumetric energy density to natural gas. These

4	Highly Efficient when Compared to Other Energy Sources	Hydrogen fuel cells are more efficient than many other renewable and non-renewable sources, including hence more output per of fuel input e.g. conventional. combustion-based power plant has about 33-35% efficiency compared about 65% for hydrogen fuel cells while vehicles with hydrogen fuel cells use 40-60% of the fuel's energy and offer 50% reduction in fuel consumption.
5	Almost Zero Emissions	Hydrogen based fuel cells do not generate greenhouse gas emissions compared to for fossil fuel sources, making them a clean source of power for the global energy transition.
6	They can be used to reduce Carbon Footprints	Fuel cell operating on hydrogen do not directly emit greenhouse gases which imply that the operation stage of fuel cells has no carbon footprint hence an ultimate choice in low carbon transformation of energy sector.
7	They can afford Fast Charging Times	The time taken to charge time for hydrogen fuel cell power units is as short and the time needed to refuel a conventional internal combustion engine (ICE) car i.e. as flow as 5 minutes to charge and much faster charging the battery-powered electric vehicles which between 30 minutes and several hours to charge, which provides flexibility as conventional cars.
8	No Noise Pollution	Hydrogen fuel cells are noiseless devices compared to wind and thermal sources of power like internal combustion engines hence they are much quieter than many other power sources
9	No Visual Pollution	Wind, biofuel, and some other low-carbon energy options can be an eyesore to users and the environment, but not for hydrogen fuel cells hence fuel cells have limited or no visual pollution issues.

10	Rural and remote areas application	The availability of hydrogen through local generation and storage will gradually substitute diesel-based power and heating generation in remote and off grid areas. This will improve the lives of rural poor and offer pollution free energy options.
11	Long Usage Times	The fuel cells offer greater efficiencies about usage times with a hydrogen vehicle having the same range as fossil fuels of about 300 miles, which is superior to electric vehicles. The performance of hydrogen fuel cells is not significantly impacted by the environmental or outside temperature and doesn't diminish in cold weather compared to electric vehicles.
12	Versatility of Use	Fuel cells have potential applications in a wide range of stationary and mobile applications e.g. hydrogen powered vehicles, cogeneration, and domestic applications.
13	Democratization of Power Supply	The hydrogen fuel cells have significant potential to reduce the consumption of fossil fuels, hence democratize energy and power supplies globally. Reduced use of fossil fuels will limit the avoid the problem of fossil fuel prices increase and stock reduction rate.

From Table 15-3, it is noted that there are various benefits of fuel cells, like the democratisation of power generation, which is a shift from traditional source, long usage durations in transport application, high conversion efficiency and clean source of energy.

15.14. Disadvantages of Fuel Cells

The production of green hydrogen by electrolysis is a high energy process while the use of renewable energy sources remains a costly option and accounts for a low of about 5% of total hydrogen production globally. A vast majority of global hydrogen production is derived from

fossil fuel sources through methane reforming processes, and this is expected to remain the most feasible option for many years as the capacity for more efficient and cost-effective electrolyzers increases and reduce the production costs. This is a drawback to the fuel cell technology as a truly green energy option[308]. Other disadvantages of fuel cells are.

- i.) It has high initial investment cost
- ii.) It is associated with low voltage.
- iii.) Fuel cells have lower service life [973]

15.15. Conclusions

A sustainable fuel cell and hydrogen energy industry will depend on the reduction of costs in hydrogen production, the development of hydrogen refuelling stations and higher fuel cell efficiency to lower cost of energy conversion. Fuel cells convert chemical energy of in fuel efficiently to electricity without combustion, with low emissions compared to conventional equipment/techniques. It is therefore a fuel cell defined as an electrical chemical device that directly converts chemical energy to electricity. The three main parts of a fuel cell assembly are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit. Fuel cells development partially focuses on optimization of catalytic the layer Of the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available.

The theoretical thermodynamic efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60%. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2 , O_2), hydrazine (N_2H_4 , O_2), carbon/coal (C, O_2) methane (CH_4 , O_2). Fuel cells employ an external or internal fuel-reforming process using any hydrogen-rich fuel can in different types of fuel cells. Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO_2 emission. Since fuel cells are not subject to the limitations of the Carnot cycle

efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines. The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cell's reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85%

The major technological challenges that must be overcome for a transition from a carbon-based (fossil fuel) energy system to a hydrogen-based economy are cost of efficient and sustainable hydrogen production and delivery remain high and should be reduced, need to develop new generation of hydrogen systems for automotive applications e.g. refuelling stations across the transport networks and need to reduce the cost of hydrogen fuels and hydrogen-based systems. An integrated hydrogen energy system of the future should combine small and large fuel cells for industrial and domestic decentralised heat and electricity power generation with extended hydrogen supply networks that can also fuel conventional internal combustion or fuel cell vehicles.

15.16. Recommendations

Rapid deployment of fuel cells should be undertaken by countries seeking to achieve the climate and emissions targets as set in the Paris Agreement. With decentralization of generation, fuel cells will play a critical role as a source of baseload power in microgrids. Use of fuel cells should also be scaled up in the transport sector with coupling of transport sector where fuel cell cars can also supply power to the grid via the V2G technology infrastructure. However, the sustainability of fuel cells depends on the source of hydrogen. Development of green hydrogen should be scaled and made cost competitive while biomethane can be used to coupled fuel cells to vast biomass resources.

CHAPTER 16:

SMART GRIDS AND MICROGRIDS IN THE ENERGY TRANSITION

16. Overview

The contents of this chapter are published in [16, 61, 147] as conference papers and journal papers on smart grids and microgrids in the energy transition. The smart grid is a product of the advances in computer and communication technology and power electronics that creates a more resilient, reliable and one that supports a two-way flow of electricity and information. The smart grid enables more uptake of the variable renewables like wind, solar and variable loads like the plug-in cars and improves the efficiency of power systems and facilitate several products and services supported by the grid like automatic healing and re-routing of power in case of a fault and demand side management. The deployment and use of smart grids and microgrids will enhance the realization of shared goals of grid stakeholders, promote energy security, enable economic growth, and help in the mitigation of climate change.

16.1. Introduction

The growing electricity demand, expansion of the grid and high number of power plants and electricity customers have continuously increased the complexity and challenges of the electricity grid in delivering quality and reliable electricity to end users. These challenges require greater system reliability, improved efficiency, more energy security, cleaner environment, and higher system sustainability which can be achieved by use of smarter electricity grids. The smart grid is a rapidly growing concept in the electricity industry that has potential to transform the use of variable renewables, variable loads and improve energy efficiency in grid power systems. The Smart grid is the direction and trend of power industry development based on the physical grid that combines advanced information & communication technology with operation technology the traditional grid to form a smart system. The main links covered by the smart grid are power generation, transmission, system transformation, power distribution, electricity consumption and dispatch[16, 61, 147].

The smart grid coordinates the needs and functions of different participants in the grid environment enabling the system to operate on the premise of ensuring system reliability and stability. The smart grid technologies have demonstrated potential to revolutionize the electricity grid by means of two-way communications to improve power system reliability, economy, efficiency, and sustainability in power generation, transmission, and distribution.

Smart grids facilitate the optimization of the electricity mix consisting of both renewable and non-renewable sources by application of computer programs and hardware to manage power generation, transmission and distribution resources, smart grids facilitate optimization of the electricity mix of both renewable and non-renewable energy sources for sustainable power generation and supply through existing power system infrastructure[16, 61, 147].

The smart grid technology is a product of the fourth industrial revolution (4IR) and is necessary to accomplish fastest technological reformations in electricity generation, transmission, and distribution (T&D) because of growing application of computers, sensors, sensors, and communications. By plugging the Internet of Thing (IoT) in the traditional electricity grid, the resulting smart grids can optimize energy solutions through flexibility in the management of the diverse energy systems, enhance operational insights, improve maintenance forecasting and self-healing abilities, and create more a more secure and safe power system. The study recommends conversion of the traditional grid to smart grids as a technical solution with significant financial/economic, social, and environmental benefits in the sustainable energy transition. To realize this, it is necessary to build the institutional capacity and put in place policy measures that promote the development of smart grids this like micro grids, modern energy storage, decentralized generation and development of renewable energy resources and technologies[16, 61, 147].

16.2. The Traditional Grid

The traditional grids simply transmit power generated at central power stations with voltage. transformers that increase and reduce voltage to supply electric power to consumers. The traditional grid is undergoing substantial growth which calls for a reliable grid operation and maintenance with a more efficient and sustainable consumption of electricity. As a result, the conventional power grid is being transformed to a smart grid (SG) which supports a diverse, heterogeneous operating measures and devices like smart appliances, smart meters, and renewable plug-in vehicles, energy resources generation systems[16, 61, 147].

16.3. Smart Grid Products and Services

Unlike the traditional grid, smart grids, perform the functions of the traditional grid and added ability to remotely monitor all activities or faster and better responses and performance of the power grid [61, 974]. Globally, smart grid technology can address the energy sustainability and transformation challenges like over reliance on fossil fuels, large gap between demand and supply and limited access to renewable energy resources. If well

addressed, they will enable a smooth transition to the smart energy systems[974]. The specific products and services or smart grids are as follows.

16.3.1.NET Metering

Integration of renewable energy sources with smart grids means that power can flow in either direction. Smart meters have capacity to meter both flows compute the net energy at the consumer premises. Smart meters can measure three important components of energy i.e., kWh, kVArh and kVAh. The smart meters are also equipped with communication facilities for two-way exchange with the control center, to transfer data and receive control commands[618]. Net kWh curve represents the difference between import kWh curve and export kWh curve, where the positive indicates that the consumer imported more than he supplied to the grid, while the negative portion shows that the consumer injected more power into the grid than he imported. [30].

16.3.2.Time of Use (TOU) Metering

This metering or billing system is based on the time that power is consumed with higher charges during the peak and lower charges during off-peak to facilitate better load management[618]. The TOU tariff helps shift load from the peak load time to off peak period which has potential to increase the performance of the system by reducing maximum flow through the system. as maximum power flow in the network would be reduced and reduce pressure on power generation. which often use fossil fuels sources for peak supply.

16.3.3.Peak Load Shaving

Peak load is an important factor for power grids because it only for a small percentage time duration in a day and requires extra generation capacity which is economically feasible and is inefficient use of generation capacity required for just limited time[975]. Peak load shaving refers to the shifting loads from peak periods to off peak periods. By use of smart grids, it is possible to shift various demand to operate within minimum ranges. Smart grid facilities create flexibility and demand shifting leading to load management, peak shaving and energy saving through moving loads from peak period to off peak periods. The Peak load benefits both consumers and the utility operators[618].

The growth in peak load increases chances of power failure and increases the marginal cost of electricity supply hence the increasing need to reduce peak demand. Peak demand is often met by gas turbine and diesel engine power plants which is expensive power and polluting

from greenhouse gas emissions. Therefore, peak load shaving has economic and environmental benefits. And is achieved mainly by three different strategies namely.

- i. Integration of Energy Storage System (ESS)
- ii. Integration of Electric Vehicle (EV) to grid
- iii. Demand Side Management (DSM)

16.3.4. Advantages of Smart Grids

16.3.4.1. Billing Efficiency with Smart Meters

A smart meter is an electronic a device used for measuring natural gas, water or heating. The smart meter is equipped with real-time or near real-time sensors, outage notification, and ability to monitor power quality. Smart meters are similar in many respects to Advanced Metering Infrastructure (AMI) meters. As opposed to interval and time-of-use meters smart meters have automatic reading ability [976, 977].

A smart meter records energy information like electricity consumption, voltage levels, electric current, and power factor and communicates to the consumer thus ensuring clarity on consumption behavior. They also communicate with the utility company for system monitoring and billing. The smart meters facilitate a two enable two-way communication between the central system and the meter[977].

The smart meter differs from automatic meter reading (AMR) due to its ability to effect two-way communication between the meter and the supplier. The communication facility in smart meters is achieved through wireless, or fixed wired connections. Common wireless options for smart meters are cellular communications, Wi-Fi (readily available), wireless ad hoc networks over Wi-Fi, Wi-SUN (Smart Utility Networks, wireless mesh networks, low power long-range wireless (LoRa), Wize (high radio penetration rate, open, using the frequency 169 MHz), and ZigBee (low power, low data rate wireless) [976]. Smart grids make use of smart meters as the backbone in the development of smart grids. have made billing free from manual operation as opposed to the traditional billing cycle usually done once a month by many utilities. With smart grids billing can be done over shorter cycles like 30 minutes and in some cases, prepaid services are available. Accuracy in metering is also significantly improved by smart metering and in some up to 655 improvement has been achieved by conversion from manual to smart meters which reduces commercial losses[618].

16.3.4.2. Power Quality Control

The integration of renewable resources via power electronic devices into the grid is one achievement of smart grids. Variable renewables introduce harmonics into the power system which can deteriorate the quality of power. Smart grids use automatic power factor correction (APFC) devices and active filters to improve the power factor and power quality. The Installed Automatic power factor correction devices are equipped with modern communication functions for regular reporting to the utility control center[618].

16.3.4.3. Outage Management

The smart grid has the Outage management system (OMS) which can enhance the reliability of the power systems by application of the grid smartness for operational benefits like power restoration, reliable and cost-effective services. This is technically achieved by incorporating AMI, DA, ICT and other smart devices in the smart grid power system [618]. Outage management can be realized by distribution transformer monitoring system (DTMS) and in addition fault passage indicators (FPI. In some typical installations, DTMS systems is equipped with oil sensors, palm sensors, CT and PT. The Distributed Transformer Monitoring System can measure all phase current loadings, transformer oil levels and temperatures of DT. [618].

16.3.4.4. Loss detection

The use of smart meters to collect, compute, store, and transfer energy data to control center occurs at constant intervals of say 30 minutes. Power losses can be determined by comparing the energy data at different nodes and DT terminals, power. This enables quick measures to restore power to consumers [618]

16.3.4.5. Tamper analysis.

Tampering of meters includes deviation from defined limits some fault or malpractice or damage on the metering system. Smart meters are designed in a way that that they send a signal to the server and information to all parties concerned in the event of tampering in the form of SMS and e-mail and SMS alerts. Examples of t tampering cases include over-current, terminal cover open and flow of current through the earth. Tamper alerts facilitate quick and specific response by authorities from the utility company. Through tampering cases, consumers may be drawing current than the limit, the meter may change locations without prior information or authority, the meter itself may be faulty hence malfunction. Other tempering cases include bypassing the meter and connecting undesirable loads[618].

16.3.4.6. Better Reliability

The reliability of a power system depends on customer needs and is measured as ability to meet customer needs. Therefore, a reliable power system implies having a flawless and errorless system continuously supplying power to consumers. This is achieved in Smart Grid by the ability to detect faults and self-healing potential of the system. The limitation of the conventional grids is with regards to interaction of renewable resources, support of micro grid and demand response. Smart Grids can monitor all information and data and can establish system reliability. It is possible to monitor hybrid generation and management of the grid remotely which improves reliability. Smart grids make use of technologies like Dynamic Stochastic Optimal Power Flow (DSOPF) which make it possible to estimate and optimize power flow in the system. Therefore Smart Grids can improve system reliability through enhanced metering and communication[97].

16.3.4.7. Demand Side Management

Demand side management refers to programs and measures that can be used to influence consumers to balance their consumption and generation capacity of the utility [975]. Demand-side management is a direct effect and benefit of smart grid systems whose key objective is to allow the utilities to manage consumer loads. An important feature of demand side management is the development of incentives for smart customers to modify their temporal use of power to reduce peak loads. Demand side management is strongly connected to demand response models, as programs that seek to shape the demand and supply to achieve an efficient power system. Interconnection of consumers, micro grids, electric cars, as well as utility companies can only be made possible by means of efficient and effective demand-side management [316] Demand side management is categorized into two main parts: namely energy efficiency and demand response.

16.3.4.8. Energy efficiency

Energy efficiency refers to the use of less energy economically to provide same or better services to customers[975]. Energy efficiency is important as it ensures sustainable use of energy resources by reducing a country's dependence on imported and expensive energy resources and serves to increase the awareness on environmental challenges which is a key requirement for sustainable development [978]. Use of smart grid technologies helps in dealing with intermittent power and the low power system utilization efficiency. Smart grid techniques increase the amount of intermittent renewable generation in power system, by

increasing the capacity of grid-connected clean energy like solar energy, wind energy and photovoltaic system while at the same time promotes energy saving in power system. Therefore smart grids improve the power system efficiency by improving the utilization efficiency and the power consuming efficiency of the power systems[561].

16.3.4.9. Demand response (DR)

Demand response refers to the change in electricity consumption using the demand-side resources away from the normal consumption patterns as a result of response to applied changes in electricity price over time, or as a result of application of incentive payments that are meant to motivate electricity price reduction meant to avoid the system reliability from being jeopardized[975]. Demand response is the ability of residential, commercial, and industrial sectors to modify energy consuming models in response to variations [979]. Demand response plays a very important role in peak shaving to balance generation and consumption. There are various demand response techniques that can be adopted to shave peak load e.g., incentive based direct load control programs through lower pricing or coupons [975].

The two-way communication provided by smart grids enable consumers to interact with the grid and other stakeholder which provides an opportunity a more economical use of grid power and hence higher efficiency and reduced peak time stress by shifting load and self-generation. The demands of side management options focus or rely on adequate communication between utility company and end users, a facility that is provided by smart grids. With further evolution, scheduling of consumption by end users will enable the distribution system to schedule resources based on requirement. The system also provides financial incentives by scheduling consumer needs[97].

Demand side management (DSM) is an important feature of smart power grids that can be defined as a set of techniques applied to modify the electricity consumption pattern by end users. Demand side management methods motivate consumers to optimize energy consumption and reduce energy costs and improve efficiency. The benefit to consumers is to reduce electricity energy bills but energy systems or utilities benefit through demand shifting from peak to non-peak hours. The DSM actions are applied in smart meter management to control the load profile of the of consumers to realize efficient utilization of power plants. The Smart grids overcome support help address challenges of conventional electricity grid

through support for new concepts and technologies like, renewable energy resources, distributed power generation (DG), smart meters, and energy storage [111]

Smart grid facilities have also led to the development of smart devices which could communicate with the grid and make the consumer or facility more autonomous through effective and efficient use of power or energy resources. Smart appliances can shift demand of household electricity to off-peak or low-price periods. Which saves on cost of power for the consumer. Household appliances can also be remotely operated by means of networking protocols like 'ZigBee' which provide a solution to have a wireless control. These protocols facilitate communication and coordinate with all the stakeholders in the energy management system thus they provide optimal solution to the use[97]

The smart grids are of significant benefit to the Retail Electricity providers (REPS) who can make use of demand response programs. REPS fill the space between wholesale electricity markets and final consumers. REPS use forward contracts and can purchase part of the consumer demand through the pool market. The retail electricity providers face financial risks from factors like volatile loads, price variations, and actions of generating companies with market implications. However, REPS can manage these risks by employing demand response programs. For example, reps can propose selling price based on fixed tariffs, time-of-use price, or actual time price during the contract period. Power end users can shield themselves against financial risks by long-term contracts with REPs. Therefore, REPs can apply a blend of methods to control the financial risks from wholesale markets by means of well-designed demand response program (DRP) [979].

To implement demand response, it is necessary for consumers to have smart meters. Demand response plans can be exploited by retail electricity providers as an alternative allowed through smart technology to enhance the anticipated benefits of varying demand. Smart grids provide intelligent technologies in grids and home energy management systems, for moderation of financial risks. REPs can also use distributed generation and ESS (energy storage system) they possess to manage costs and financial risks and these resources can effectively be managed smart grid systems[979].

16.3.5.Decentralised Generation

Several recent advances in energy technologies and grid infrastructures have increased the interest in the use of distributed generation (DG) resources for grid electricity generation. The exploitation of distributed generation (DG) for grid electricity is subject to technical

constraints to extend distribution and transmission networks to some areas as well as the deregulation of the electric power sector. There are many benefits of distributed generation depending on the characteristics of the sources like photovoltaic (PV), diesel engines, wind power systems, type, and characteristics of the loads, availability and access of local renewable resources and power grid network configuration. The benefits can be technical, environmental, social, political, and economic benefits like line-loss reduction, system reliability improvement, local revenue, employment and economic benefits and reduction in environmental pollution. The various benefits can be optimized by optimal sizing, optimal location, as well as optimal configurations [580]

16.3.6.Smart Micro-grids

Micro grids are defined as electrical networks with ability to operate in isolated mode or grid-connected mode and have their storage units, whose size and capacity depend upon the extent of integrated distributed generation[56]. A micro grid is a group of localized generators, loads and storage devices, and loads which can play an important role in the context of the smart grid because they can be integrated into the main grid and can also supply loads connected during islanding situation[980]. Micro grids are linked to distributed generation (DG) which has become important because of growing interest in reliable and sustainable energy supply based on more renewable and alternative sources of energy with the objective of reducing stress and losses in power systems. The objective of decentralized generation is to meet local electricity demand by using different energy sources in the power system. This is achieved by development of micro grids which constituted a controlled system of loads and distributed energy sources meant to supply power to the local neighborhood[316]. A micro grid can be said to be a smart power network designed to operate independently from the main or central grid but can also be synchronized to the main power grid besides having ability to operate autonomously. Micro grids supply energy obtained by means of distributed energy resources (DERs) to nearby consumers. It is therefore a local form of energy. Micro grids have emerged as the power system of the future with significant ongoing improvement. Several demand side management programs can as well be implemented in micro grids for energy management [111].The U.S. Department of Energy defines a micro grid as “a group of interconnected loads and distributed energy resources (DERs) that have well defined electrical boundaries that can operate as a single controllable system within the grid and used to connect and disconnect from the bigger or main grid hence can operate in both grid-connected and island modes”[316]. A distributed energy system qualifies as a micro grid if it

obeys the three criteria that includes having own electrical boundary, have a main controller for the subsystem and have power generation capacity that is higher than peak load and additionally can operate in island mode. Therefore a micro grid has capacity to supply enough power in island mode but is still connected to the main or wider grid[981].

The concept of a micro grid is a result of the proliferation of distributed resource (DR) in the form of distributed generation (DG), or distributed storage (DS), or a combination/hybrid of distributed generation and storage which can be operated in three modes namely grid connected mode, islanded or autonomous mode or between the two modes of grid and island modes. Micro grids are expected to have multiple generators and loads operating reliably and economically viable as operational power systems [982]. The sustainability of micro grids is significantly enhanced by the development of smart grids.

Micro grids are designed as small and autonomous subsets of the main electricity grid, which help reinforce the self-healing characteristics of smart grids[983]. Smartening of electricity grids by installation of intelligent systems and applications into the grid infrastructure improves their reliable, efficiency and capacity to integrate variable renewable sources of energy[109, 226]. The smart grid achieves operational efficiency by means of distributed monitoring and control, and energy management. Use of micro grids with smart facilities bring renewable sources of energy into the mainstream, besides increasing efficiency and optimal use of grid facilities through demand response and peak shaving. Micro grids introduce resiliency and autonomous re-configurability in the electric power grid to guard against man-made and natural disasters [983] which is an ultimate benefit of smart grids.

Operationally, micro grids can be defined as low voltage intelligent distribution networks made up of distributed generators, energy storage devices and controllable loads which can be operated as interconnected power systems with the main power distribution grid. They can also be operated as islanded systems if they operate independently or are disconnected from the main power distributed grid. From the point of view of the main grid, micro grids are said to be controlled entities within a power system with ability to be operated as a single aggregated load and as small sources of electricity or ancillary services that support the main grid. To an electricity customer, a micro grid is viewed as a traditional low voltage (LV) local distribution network supplying electricity. Properly deployed micro grids improve local power system reliability, reduce emissions, support local voltage hence power quality, and reduce costs of power supply. Different micro grids may be unique in terms of source of power, type of load. Different micro grids could have different types of

load and energy sources. Therefore micro grids can enable energy resource sharing [983]. Energy or power sources for micro grids includes dies engines, micro or mini-turbines, fuel cells, wind turbines and photovoltaic sources.

A micro grid (MG) refers to a distributed energy resource having energy storage facilities and controllable loads and having ability to operate as a self-sufficient energy network. They help to improve reliability, resilience, flexibility, and accessibility renewable energy resources with ability to optimize and implement demand response programs [984]. Use of many micro grids in a power system with many energy sources leads to large amounts of data to process and handle. The solution to these challenges is the use of an architecture with a significant degree of intelligence across the grid for effective and efficient electricity distribution. With smart grids, the micro grids are not used as centralized units but instead they operate as individual systems connected to the main grid by means of individual intelligent nodes[97].

The main challenges facing micro grid design and operation is the use of many small generators with different capacities and characteristics, lack of a dominant and more reliable source of energy during island mode of operation and high demand or need for very quick response for electronically interfaced generator units which has adverse effect on voltage/angle stability if not properly managed. These critical challenges require a power management strategy (PMS) to facilitate a reliable or sound operation of a micro grid with multiple generators especially during the island operation. Compared to the large interconnected grid, a micro grid needs faster response of the power management strategy(PMS)[982]. Distributed energy sources interfacing with a micro grid can be achieved by use of rotating machines or electrical coupling using power electronic converters that provide coupling media with the main or host system[316]. The converters are connected parallel via a micro grid. Circulating currents are prevented using droop control methods to prevent circulating currents among the converters without critical communication between them. However, the main challenge of droop control method load-dependent frequency and amplitude deviations which can be solved by installation of a secondary controller, in the central control of the micro grid[316].

The role of the PMS in a micro grid is to assign real and reactive power references for generator units, quick response to disturbances and transients and establish the required power generation set points for all the generator sets and provide a means of resynchronization of the main grid and the micro grid [982]. Since PMS is a function of a

smart grid, it is demonstrated that the development and harmonious operation of micro grids is dependent on the level of smartness of the power systems involved. The various technical and management experienced by micro grids can be solved by application of smart grid components like introducing smart technologies like energy storage devices, use of advanced metering infrastructure (AMI), application of smart appliances, integration of computational intelligence, application of demand response management, and the Internet of Things (IoT) in operation of micro grids[56].

16.3.7.Integration of Renewable Resources

Renewable energy sources, particularly wind and solar are huge but variable and intermittent making exploitation to meet the demand difficult. Electricity from renewable sources can from solar, wind, battery storage devices can meet the growing electricity demand and reduce emissions with the right technology in place. The ideal location of these renewable resources may be far from a functional grid for transmission and distribution making exploitation impossible for conventional grid delivery. Under such circumstances, micro grids become the best option to distribute renewable electricity from these widely distributed sites that can be joined together to form a bigger electricity distribution network [97]. Whereas the wind does not blow every time and the sun does not shine always, providing information on electricity demand and weather forecasts made possible by use of smart grids, helps the grid operators to plan for the integration weather dependent renewable energy to the grid and hence stabilize or balance the electricity networks. [985].

The grid needs conventional back up power and huge energy storage so as it can accommodate more renewable energy would need large quantities of conventional back up power and huge energy storage. These is necessary to accommodate the natural variations and intermittence of energy supply in terms of time of day, and season.[986]

To realize commercialization and commercialization and large-scale use, of renewable energy systems like solar and wind, needs to address issues related to design and sizing of the system, effective and suitable technical and financial models, balance electricity price for integrating the renewable sources. Balance electricity price for integrating PV in a smart grid system dealing with challenges of using variable renewable systems are limited for several countries[986]. The development of power electronics to handle variable electric power by fast semiconductor switching using IGBTs has a significant role to play in the integration of renewable energy sources. The challenge of power electronic circuits is that they may cause

harmonics in the power system. As a solution, FACTS devices which include static synchronous compensator (STATCOM), static series synchronous compensator (SSSC) and unified power flow controller (UPFC) can help to improve the stability and reliability of the grid having renewable energy sources. These systems provide filter circuits which mitigate the harmonics injected in the grid caused by power electronics circuits. Additionally, use of real-time computer controllers equipped with advanced and complex algorithms facilitate maximum extraction of renewable energy power and reduce fluctuation in renewable energy generation. besides protecting storage devices like batteries from over charging which enhances the storage battery life. Renewable energy generation fluctuations can also be adopted by distributing energy generation from a larger geographical area in small power plants instead of large power plant in few places. The challenge of huge land needs can also be taken care of by adopting distributed generation from renewable energy resources[317].

16.3.8.Reduce Transmission and Distribution Losses

The purpose of electricity grids is to transport electricity to the consumer's point by performing four critical activities. These activities are supporting generation, transmission, distribution and retailing of electricity. The traditional power system involves use of large power plants to generate electricity located several kilometres away from consumers and hence must be delivered to distribution networks via long transmission networks where transmission losses are experienced. In modern grids electricity is produced in small power plants connected to the distribution grid, in an arrangement referred to as distributed generation (DG). In distribution networks, power is delivered to consumers via low voltage (LV) distribution lines up to the electricity or energy meters [579, 987].. Retailing of power oversees or responsible for electricity billing. Energy is always lost through the components of the power systems like cables, electric transformers, etc.[987]. The shorter the length of travel and resistance, the less the power losses.

Power transmission and distribution losses refers to deviations between electricity generated and electricity delivered to consumers, for reasons that are technical and nontechnical in nature. For many reasons, different countries have different levels of transmission and distribution losses[988]. The global average for transmission and distribution losses is about 10%, Sub-Saharan Africa (SS) has average of 18% while some countries have extremely high losses e.g., Togo has about 29% and Congo has average of 33%. The electricity transmission and distribution losses have increase the demand on demand on power plants to meet the losses in power which has a significant impact on the environment due to increased

emissions associated with the increased demand on generation[988]. Consumption out of the meter is another common loss classified as non-technical energy losses (NTLs), which affects for total electricity demand, electricity quality and overall income of the power system[987].

The main reasons for losses in power distribution are theft and a weak electricity grid. Theft can be reduced by positive interaction between all stakeholders which can facilitate awareness about the benefits and motivating the consumers to be active participants where they see benefits from connecting to the grid as well as use of modern technology and infrastructure. Smart grid Infrastructure and devices like energy meters in every bus for power system, monitoring can help the authorities to detect and control electricity theft.[317]. Therefore, smartening of the electricity grid will reduce transmission and distribution losses leading to efficiency and reduced avoidable generation as well as related emissions and environmental pollution.

Since electricity consumption by end users varies over the day, consumption has direct implications on electricity losses. Since demand-side management seeks to reduce peak hour power consumption, the effect is to reduce network congestion and system losses. From the perspective of generation, the distributed generation modifies the traditional, unidirectional, downward flows in electricity system and so it directly affects power transmission and distribution losses as energy is produced at voltage network which is close to the consumers[987].

16.3.9.Smart Homes and Internet of Things (IoT)

Smart homes refer to buildings which may be offices or residential that are equipped with intelligent devices and distributed generators with advanced control systems, whose objective. is to maximize internal energy consumption during high demand times. The objective during low demand times, is to export the excess energy in a Smart Building to the grid and support it while generating valuable income for the investors or owners of the buildings[35, 360]. The main components of a smart home system are distributed generators, consumer electronics like laptops and lighting bulbs, storage and electric vehicles and smart meters, chargers for electric vehicles and different loads being served[12, 989].

Advances in technology have changed the way energy is produced, stored, saved, and consumed, laying the ground for the deployment of smart energy systems. Incorporating the Internet of Things sensors, digitization, distributed generation, micro grids, and automation is creating a new smart energy ecosystem like smart grids. .Just like the internet facilitates

information flow and data interchange between computers connected to the same network, the smart grid is also powered by a web of interconnected electric grid devices[61].

In general, the IoT refers to a collection of internet-enabled devices that facilitate the collection of data and information, data pipelines, and the real-time information transmission between devices and other people. [60, 562]. Therefore, the Internet of Things (IoT) is a connection of people and things at any place and time, by use of any network and any service. It is further said to be a global network infrastructure of Internet-enabled entities with web services. The smart grid is a data communications network which is integrated with the power grid to collect and analyze data that are acquired from transmission lines, distribution substations, and consumers [990]. Smart grids are a typical application of Internet of things (IoT) technology in electricity sector and if well implemented can resolve several challenges facing the traditional grids like security of supply, outages, high greenhouse gas emissions, and other issues. [60, 562].

The facilities that enable the operation of Internet of Things (IoT) include sensors, actuators, RFID tags or any device that requires a communicating interface and a computing ability, into the Internet. It is now possible to access, manage and communicate through the internet - based protocol like IPv6, UDP/TCP, HTTP, and others for objects like fridges, heaters, windows, switches, washing-machine, etc. For devices compliant with the IEEE 802.15.4 standard, the IETF (Internet Engineering Task Forces), several protocols are proposed for their efficient integration and at different layer to the Internet. These protocols include Constrained Application Protocol (CoAP) which is a specialized web transfer protocol used with constrained nodes and constrained networks; Routing Protocol for Low-Power and Lossy Network (RPL), and IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN) which is an adaption layer used to support the IPv6 protocol on IEEE 802.15.4 networks. For functions that cannot support internet protocol (IP) or functions that cannot be updated to support the internet protocol, gateways where proprietary non-IP stack protocols like Zigbee v1, HART, Z-Wave, etc., are translated to/from IP stack protocols can be used but are expensive [991].

Smart grids can use wireless sensor networks (WSNs) unlike the traditional communication technologies since it is cheaper, fast to deploy, has high flexibility, and has aggregated intelligence via parallel processing capabilities[61, 992]. The internet of Things in smart grids refers to the application of WSNs, smart meters, actuators and components with information and communication technology (ICT). The main limitation or challenge with integration of

the IoT technology within the smart power grid introduces the cost of large data processing. The data includes end users load demand, power lines faults, network's components status, scheduling energy consumption, forecast conditions, advanced metering records, outage management records, and enterprise assets. Smart grid utility companies should be equipped with software and hardware capabilities to efficiently handle data collected[992].

The internet of things applies bidirectional flow of energy and information within the smart grid to get deeper insights on current and future/predicted actions whose aim is to improve energy efficiency and reduce overall cost. Big data technologies must be adopted by the smart grids for accurate monitoring and scheduling, information from the grid within short intervals[991, 992]. The ICT infrastructure should have a high degree of reliability to avail available data for information extraction needed to perform critical functions like fault detection and fault resolution. Security is an important requirement for the ICT to avoid or limit failures from cyberattacks or by combined attacks to the grid and ICT infrastructures. It is necessary to guarantee high reliability for the health and industrial systems.[566, 992]

The internet of things (IoT) is used to describe common items like medical wearables, housewares, and equipment the monitor users' physical condition, automobiles and tracking devices among others that are connected to the internet and identifiable by other devices in the system. Through the internet of things, it is possible to collect data from connected devices and products and determine the usage by and use the same in energy planning and market campaigns. At industrial scale, farmers can apply IoT sensors into fields to monitor and hence control soil parameters like nutrients or fertilizer use and needs[993]. The Internet of Things (IoT), Internet of Everything (IoE) and Internet of Nano Things are new approaches that incorporate the internet into personal, professional, and societal life. 'Internet of Things' or 'Internet of Objects' represent electronic or electrical devices that vary in size and ability and are connected to the internet in a way that goes beyond mere machine-to-machine communication. Through internet of things, one can access information any time wherever you are connecting devices via real-time information generated by the interconnected devices[616]. Smart homes are an important segment that has significantly been affected by the Internet of Things. Smart home-Internet of Things is a new domain created when smart homes are connected to the IoT [994]. The main benefits of smart homes are energy efficiency and comfortable living. Smart homes are created by integrating ICTs and energy technologies for home or end user applications.

A smart home refers to a residential environment where information and communication technologies are applied by the resident for convenience, security, entertainment, and comfort needs. This enables home owners to employ well-designed management functions for optimal control and maintenance of their homes[994].Through integration of recent and modern Information and Communication technologies (ICT) and energy technologies in the housing environment gives rise to new applications and services. Examples of technologies in smart homes include ubiquitous computing technologies, that make it possible to connect objects anywhere and at any time, and apply small sensors to provide information to entire network systems making users part of the network [995]. Therefore, users become part of a system of interconnected computing machines sharing information via the network without traditional forms of communication which is the main concept behind the IoT. Therefore, based on the IoT environment, equipment or home users can interact with objects or devices and services in smart homes[994, 996].

Internets of Things (IoT) uses computation and communication technology to make life easier, automatic, and handy by exploiting the internet revolution. The development of the smart grid and its components have created demand for technology to enable interaction with system components efficiently, reliably and in a smarter way, although these technologies come along with new security challenges like threat of data tampering, impersonation, overdoing, privacy breaches, authorization, and cyber-attack [32]. This implies that the smart grid-based Internet of Things (IoT) requires services like authentication, data confidentiality, user's privacy, and data integrity to avoid any security risk [32]. The use of IoT facilitates enhanced customer experience and efficiency of service delivery by enabling flexibility and easy interaction with the grid which leads to cost reduction. It is therefore observed that the IoT further makes the smart grid smarter[97, 296].

The Internet of Things (IoT) has enabled the evolution from connecting people and machines to connecting smart objects, hence the IoT communications has evolved to M2M communications with objects in the IoT system being anything/device/entity that is equipped/embedded with computational, storage and communication capabilities through sensors, mobile phones, actuators, laptops, printers, computers, car, fridge, ovens among others. Smart objects in the IoT are interconnected via proprietary non-IP solutions in different applications like Zigbee, HART/ Wireless HART, Z-Wave. The IoT aims at connecting objects or devices on a larger scale using IP-based solutions like IP, TCP/UDP, either directly or through gateways if at all an IP support is not possible on condition that

they can communicate or interact with each other communicating party over or through the Internet[991].

The IoT facilitates smart energy solutions needed to strengthen smart grids through functions like.

- i. Provision of real-time alerts with respect to meter, grid damage or system outages.
- ii. Modification of supply and price based on data insights Power quality monitoring and control.
- iii. Gathering information necessary for system optimization e.g. factors like tilt angle and direction of rotation for wind power system.
- iv. Greater energy savings in the system.
- v. Software installation and continuous updates to keep the system safe and functional[60].
- vi. Enhancing the predictive analysis by collection and analysis of data while at the same time varying variables like the weather, and individual panel performance in solar systems.
- vii. Attaching monitors to individual solar panels, wind turbines and other equipment providing feedback on performance to streamline maintenance

Theft detection and prevention into the 21st century

The Internet of Things (IoT) solutions are many and may be unique to specific power system. It functions through the ability to monitor important and relevant indicators to the power system like availability of energy and consumption, on a real time basis. Other than monitoring, control is another key feature of the Internet of Things (IoT), especially the ability to remotely download and as well as install critical software updates through the cloud and management of vital asset data from any location. The IoT allows businesses access real-time alerts on power system deterioration for timely repairs to crucial important infrastructure which improves the overall system efficiency[61]. The main risk of the IoT in smart grids is that it can lead to disasters as it becomes exposed to cyber-attacks, because its monitoring and control can be done over standard internet-based protocols and solutions and can rely on public communication facilities which can cause financial losses to the utility and damage connected assets [68].

16.3.10. Electrification of Transport and Smart Charging

Electric vehicles introduce both opportunities and challenges for the power systems. Peak energy demand can be significantly increased if many electric vehicles are charged at the same time or uncontrollably causing overloading and power loss. The solution is to employ electric vehicles as dynamic loads used to offer balancing services to the power system. For full realization of the capability of electric vehicles as a flexible or dynamic load, there is need to introduce smart charging procedures which can be executed by the smart grid power system[71]. The transport industry, particularly cars, is one of the biggest contributors of greenhouse gas emission, hence the need to shift to the use of electric vehicles. Electric vehicles use the chemical energy stored batteries that can be recharged for use in vehicle propulsion and powering other automotive systems[3, 21, 107]. Although various fuels and technologies are under development for the transport sector, electric vehicles represent one of the most feasible options other than using grid electricity for charging, electric vehicles have potential to act as independent distributed energy sources for the grid[566]. Electric vehicles offer an efficient opportunity to reduce carbon emissions in the transport sector and hence mitigate climate change. The share of electric vehicles in transport is increasing globally with Europe having over 15% sales share by mid-2021[100, 529, 997].

Vehicle batteries can be charged by means of the grid by plugging the vehicles to the grid and by means of regenerative braking. Electric vehicles can be classified based on charging typologies. They are battery electric vehicles (BEV), plugin vehicles (PHEV), Hybrid Electric Vehicles (HEV) and Fuel cell Electric Vehicles (FCEV)[566]. The main motivation for electrification of transport sector is that it accounts for about 30% of world energy consumption and 72% of global oil demand making electric vehicles a key avenue for greenhouse gas emissions control and the attainment of the global climate targets [566]. The main challenges facing electric vehicles include grid infrastructure, the communication, and control[97, 998]. Electric vehicles promise to play a key role globally in the energy transition because of growing concern on fossil fuel depletion and related emissions. Since vehicle battery energy is not fully used each day, they have a potential to provide peak shaving service [975]. Smart charging can be centrally done through aggregators or can be decentralized using decentralized control structures. Aggregators are used to achieve optimal scheduling of each electric vehicle (EV). In decentralized charging systems, electric vehicles choose their own charging methods without contacting the central controller or other linked electric vehicles. Smart charging using both centralized and decentralized systems can

effectively reduce energy costs and prevent the overloading of grid components by shifting peak demand[56]. The main challenges facing electrification of transport and application in peak shaving are.

- i. The electric vehicles can only deliver power to the grid when the vehicle is parked, and they are currently not widely deployed.
- ii. It is not practical for a single vehicle to meet peak load demand alone hence many vehicles and infrastructure must be deployed and controlled together by a third party.
- iii. It is a technical challenge to synchronise the charging and discharging of a multitude of electric vehicles simultaneously.
- iv. Lack of critical infrastructure for grid integration of electric vehicles especially in highly urbanised regions[975].
- v. Charging can cause direct stress to the grid as it is often done at home, commercial and public ideally designed for other applications[97, 998].

However, when parked and plugged into power grid, electric vehicles absorb energy and store it in batteries. By provision of two-way power flow capability, these vehicles can also supply power back to the electricity grid in a concept popularly known as V2G (Vehicle to Grid) concept[998].

Since smart grids are equipped with advanced technologies for communication, metering and control, they offer electric vehicles the ability to charge and act as a flexible energy source for the grid[999]. Therefore if well planned and with adherence to standards set, electric vehicles charging can improve power quality and the performance [998, 999]. An important feature or capability of smart grids is accommodation of support of electric vehicle services making them an important tool in the energy transition[21]. Electrification of transportation is becoming a reality with advances in battery storage technology and the development of smart grids. The main motivation is that the transport sector accounts for about 30% of world energy consumption and 72% of global oil demand making electric vehicles a key avenue for greenhouse gas emissions control and the attainment of the global climate targets [82, 110, 206, 566].

Electric vehicles have continued to increase globally with 10 million electric cars by the end of the year 2020. Registration of electric cars increased by 41% in 2020, even in the face of the global pandemic-related global economic downturn and reduction in car sales by 16%[1000]. About 3 million electric accounting for a 4.6% share of global sales were

realized with Europe overtaking China as the world's largest market for electric vehicle (EV). Electric bus and truck increased in numbers globally to reach 600 000 and 31 000 respectively[1000, 1001]. The global share of electric vehicles is increasing with sales rising to 15% of sales in Europe mid 2021 mainly consisting of plug-in hybrid electric vehicles (PHEV) and the battery electric vehicles (BEV) [997].

Electrification of transportation is becoming a reality with advances in battery storage technology and the development of smart grids. Therefore, a key requirement for successful energy transition via the electrification of transportation sector is the development of the smart grid. The exact amount of actual number of emissions reductions due to electrification of transport vehicles dependent on when and where drivers charge the vehicles and composition of electricity mix[3, 61, 566].

16.3.11. Smart Cities and Streetlight Automation

Smart devices are key to efficient energy management and optimization while the intelligent application of smart grid is a key requirement for the establishment of smart cities. Smart cities have been identified as the ultimate solution to complex challenges facing urban centers. Cities are important entities because it is estimated that by the year 2050, about 70% of the world population will be living in urban centers or cities[981]. There is growing interest in linking in linking interfacing items via networks. The objective of smartening devices is to enable sharing of information or access with other devices to facilitate smart decisions with available internet and communication infrastructures. Smartness of a city refers to the desire of improve the quality of life in a city and living standards of the city residents in terms of information use and communications technology (ICT) capabilities and applications, although use of ICT per se does not constitute a smart city [981]. The main challenges facing urbanization which should be resolved are shortage of resources, energy management, waste management, obsolete or aging of existing infrastructures, environmental and human health problems among others [981] .

Smart cities like Berlin are increasingly relying on high-tech innovation to deal with urban problems like transport congestion, people's participation in governance, and environmental management. City administrations are putting in place measures and strategies like opening urban laboratories, creating innovation spaces and other sites for technological experimentation to attract ICT companies and compete in the race for digital modernization

and progress. Smart urbanization is rapidly being developed in many countries and major cities globally in both developed and developing countries[1002, 1003].

Cities around the world spend significant energy resources on street lighting and traffic control. Use of smart grids can enhance efficiency, reliability and hence reduce the energy consumption on street lighting. This can be achieved by seamless connection to different suppliers' sources, use of on/off timing control facilities equipped with the ability to synchronize with an astronomical clock. Others are the use of voltage dimming facility that responds to time-setting and traffic condition. Additionally, each lamp can be facilitated with elements for power factor improvement as well as individual lamp control. This combination leads to significant saving in energy costs. Installation of street light automation (SLA) systems can lead to energy savings by as much as 50% based on experience from similar programs[618].

Smart power grids are adding value to the concept of smart cities by enabling the following services and products to urban dwellers.

- i. Efficient power transmission and distribution within cities
- ii. Better security measures and infrastructure like affordable street lighting
- iii. Faster restoration of electricity whenever disruptions are experienced.
- iv. Efficient and cost-effective service delivery through cost reduction and wastage minimisation
- v. Reduced electricity tariffs and lower energy costs
- vi. High integration of urban renewable energy sources like solar power from rooftops

The concept of smart cities is realised by use digital technologies like the Internet of Things (IoT), artificial intelligence (AI), automation, and 5G, that facilitate a two-way communication between various utilities in a smart city and the dwellers. These technologies are already in use by industries, like health care. The development of smart cities relies on key power key electricity grid technologies like electric cars, distributed energy or electricity storage, smart meters, smart appliances, smart buildings, and decentralised generation. With global smart grid technology market expected to reach \$55.9 billion by 2026, it is evident that smart grid technology has an important socioeconomic and technical role to place in the smart cities development [981, 1003].

16.3.12. Grid Integrated Energy Storage

Energy storage is a very important component of smart grids because if renewable energy is not extensively stored, its usage becomes less feasible. The main benefit of smart grids is the ability to balance the variable and intermittent renewable sources of energy whose performance in balancing is enhanced by storage of some quantities of energy by the grid. Storage is an important component of a modern grid with Japan having 15% of stored energy for the grid, Germany 10%, and the US about 2% of grid capacity. Energy storage is an important function of demand side management, with power storage being engaged in the speed of feedback, spinning reserve and frequency adjustment. Energy storage in various forms like compressed air, pumped hydro, battery, super capacitors, and flywheels have wide engineering applications and can seamlessly be integrated in smart power grids. Electric springs are examples of innovative equipment that have been developed and proved effective in supporting smart grids by considerable absorption of renewables by facilitating the harmonizing of demand-supply [46]. According to [1004] adding compressed air energy storage (CAES) to multi-generation systems can improve the sustainability and use of renewables when used with smart grids.

Energy storage technologies have significant potential role to play in achieving load leveling, like matching intermittent source of renewable energy with customer demand as well as storage of excess power for peak time use or when the variable resource is not available. Pumped hydro storage and compressed air energy storage are notable examples of mechanical methods of energy storage-based that can be used to supply peak time power. CAES is an efficient storage system that can regenerate up to 80% of the electricity production needed to support variable renewable (RES) based power plants. The energy storage systems are used to store excess energy during off-peak when power is cheap and from clean sources to compress the air and pump in umped storage for use in peak time when demand and price of power is high. For pumped storage, the water that was pumped upstream is allowed to run through turbines to generate clean power while for CAES, high-pressure air stored in underground reservoir or tank is released to drive the turbine, and supply power for peak time use or when the renewable sources decline. This is the same for pumped storage power plants [1004, 1005].

Besides the mechanical storage methods, other storage methods are battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) which can be configured as dispersed energy storage for use in vehicle-to-building (V2B) and vehicle to grid (V2G) operating

mode where stored energy in batteries is used to supply power during the peak or when renewables decline in supply. With smart grids and dynamic energy storage/management by means of V2B, V2G, and applying BEVs and PHEVs via peak load shifting, energy expenses can be controlled why demand side management can be enhanced by optimum use of the storage facilities whose functionalities can be significantly enhanced by use of smart grid technologies and products. the purchase price of the electricity for the client and vehicle owner would decrease. Technological advances in battery story and development of smart grids will ultimately make storage as a reliable source of grid electricity and hence a key strategy in the energy transition[21, 981].

16.3.13. Smart Grids and Industry 4.0 and Industry 5.0 Applications

The first industrial evolution was ushered in by the invention of the steam engine in the 18th century which significantly transformed the industry and transport sector while the introduction of electricity led to the second industrial revolution. These two revolutions paved way for mass production and mechanization of functions for the first time, and these drove social change because of urbanization[993, 1006].

The third industrial revolution was ushered in by electronics, information technology systems and industrial automation [1007]. The third industrial revolution was a result of wider use of information technology and electronics products in industry. This revolution began in the 1950s and it saw the emergence of computers and digital technology. This further accelerated automation of manufacturing and the disruption of service industries like banking, communication and energy[993, 1006].

The Fourth Industrial Revolution (4IR) or Industry 4.0 is identified with 21st century rapid transformation of technology, industries, and societal patterns as well as processes and systems because of growing interconnectivity and smart automation. The term was popularized by Klaus Schwab in 2015, who was the founder and executive Chairman of the World Economic Forum . He asserted that changes realized are more than just improvements to efficiency and express a shift in industrial capitalism. The fourth industrial revolution is a result of advances in internet of Things (IoT) and cyber-physical systems (CPS). It is characterized by the application of emerging technologies that revolutionize the production and operation systems from machine dominant manufacturing to digital dominated manufacturing and operations. It can be said to be an integration of technologies such as CPS, IoT, Big Data and Cloud manufacturing. In addition, industry 4.0 is also concerned with the

whole concept of data and resource acquisition, sharing, use, and organization that leads to faster, cheaper, more effective, and more sustainable product and service deliver [993, 1006].

The overall result of 4IR is growth in automation, better communication, self-monitoring, and application of smart machines which have ability to analyze and diagnose issues without with little or no human intervention. The revolution also represents a social, political, and economic shift from the digital age of the late 1990s and early 2000s to a connectivity embedded era distinguished by the omni-use and commonness of technological use throughout society. The fourth industrial revolution technologies have potential to connect billions of people globally to the web and significantly improve the efficiency of doing business [1007].

Through automation, systems are augmented with wireless connectivity and sensors to use for monitoring and visualisation of the entire system and process functions as well as make autonomous decisions. With the use of wireless connectivity and the augmentation of machines will be greatly enhanced by the full roll out of the 5G which promise to provide faster response and near real time communication across systems[1007].

Beyond industry 4.0. is the industry 5.0 which involves the wider use of robots and smart machines which allows humans to work better, efficiently, and smarter. The industry 5.0 will make the factories working laces for creative people to work and create a more personalised and human experience for the workers and customers through connecting man and machines. It is projected that Industry 5.0 will make it necessary for about 60% of logistics, manufacturing, and supply chains, mining, agriculture as well as oil and gas sectors employ chief robotics officers by 2025 [1007]. The operation of smart grid technology places them between industry 4.0 and Industry 5.0. but with potential to transform to industry 5.0 technology as an intelligent man machine system with automated operation.

Smart Grids provide an intelligent infrastructure that has potential to transform power systems into more secure, efficient, reliable, flexible, and sustainable energy systems. The smart grids are equipped with smart devices and smart metering like sensors and sensor networks. They are installed at multiple places along the grid like transformer customer premises, substations. The sensors monitor the state and operational health of the grid infrastructure by monitoring various parameters like temperature, quality disturbances, and outage detection. This sensing functions enable control centers to receive accurate information about the actual condition of the grid[992].

16.3.14. V2X Technologies

Electric vehicles apply an electric drive traction system consisting of one or more devices for storage of electrical energy or electrical energy conditioning devices or one or more electrical machines meant to transform electrical energy often in stored form to mechanical energy which is transmitted to vehicle wheels to drive the vehicle. This is an all-electric vehicle, or a pure electric vehicle (BEV, for Battery Electric Vehicle). Storage often require regular recharging by connecting the vehicle to an electricity grid or by standard exchange of battery[549]. Electric vehicles are designed to limit the use of Internal Combustion Engine Vehicles (ICEV) and limit dependency to oil as energy source. Energy for electric cars is stored in fuel Cells (FCs), and or Ultra-Capacitors (UCs) as opposed to fossil fuel which is stored in a fuel tank. The main components of an electric vehicle system are the motor, controller, charger, power supply, and drive train. Electric vehicles available include the lower-end electric vehicles like Nissan Leaf and higher-end electric vehicles like the Tesla Model S. The EV are cleaner, can be used in peak load shaving, reduce grid infrastructure requirements, act as mobile distributed generation or electric power, etc. but their disadvantages include limited range, need new infrastructure for development, have long charging time; and are associated with adverse battery effects[549, 550].

There are several challenges associated with charging electric vehicles via the smart grid. These challenges include overloading, imbalance, under-voltage, etc. These issues are with EV charging are managed via control called Vehicle-to-Grid (V2G) technology. The technology enables electric vehicles to charge and supply electricity and services to the grid, via an aggregator, for compensation[549]. There are several V2G technology subsets like Vehicle-To-House (V2H) where the vehicle is in the owner's residence, Vehicle-To-Building (V2B) in which the vehicle is in a commercial building. In these arrangements, the battery power supplements the electrical charge of the local buildings without transferring power to the grid in the event of power failure in the grid[549]

The V2X technologies are associated with grid connected vehicles like the Vehicle to Grid (V2G), vehicle to house (V2H), and vehicle to vehicle (V2V), where V2G refers connecting of an electric vehicle to the electricity grid for battery charging and discharge. The vehicles are referred to as grid connected EVs (GEVs) [12, 56]. The EV represents a significant and radical change in the transport sector engine driven vehicles and in the production of EV. The reason is that an electric vehicle is powered by electricity which can be generated from many sources like hydropower, wind, nuclear, wind, photovoltaic etc. An electric vehicle needs

more energy compared the electrical needs of houses for heating and lighting. On the other hand, electric vehicles can be considered as electricity storage systems for the grid. Electric vehicles store electricity that can be used during peak periods to stabilize the grid. The main objective is to meet energy needs of customers under the constraint of not destabilizing the grid [549]

As the interest in alternative sources of energy and technologies increases, there is potential for massive penetration of electricity into the grid and widespread use of DER (distributed energy sources) is expected soon. For load management and resource scheduling, a collection unit, VPP (virtual power plant) may be applied. The vehicle-to-grid (V2G) technology enables fixed or parked voltage batteries to serve as distributed sources, for storage and release of energy at appropriate times, in as bidirectional power exchange between the AC mains and DC EV batteries. The bidirectional exchange of power is realized by use of bidirectional electronic power converters connecting the grid and electric vehicle (EV) batteries. Most bidirectional converters for V2G applications use of two dedicated power conversion phases – an AC–DC two-phase conversion step that assist in modifying the power factor, followed by a bidirectional DC–DC conversion phase, to provide voltage matching.[550]. The bidirectional electronic converters, used i.e. AC–DC (BADC) and DC–DC (BDC), facilitate G2V and V2G electricity transmission between electric vehicles and the grid. Bidirectional converters facilitate high efficiency energy conversion and in the e transition from the conventional to electric vehicles, enable realization of a greener environment[549]. .

The V2G is a promising technology that enables idle or parked electric vehicles to act power plants for grid power supply, with ability to store electricity and release at appropriate times, to facilitate power exchange between grid and the electric car/vehicle. This approach increases generation capacity and improves power system stability, efficiency and reliability of the grid[550]. The development of smart grids and growth of electric vehicles has generated momentum for growth of vehicle-to-grid (V2G) technology. With V2G, one can use his vehicle to power his home, charge phones, power lights and even operate the fridge during time of high electricity price or during a grid outage and supply excess power to the grid when prices are favorable. The vehicle-to-grid technology (V2G) , which is also known as vehicle-grid integration (VGI), creates an extra power source when weather dependent renewable energy sources are not available. A home can use solar power to generate

electricity during the day but use the electric vehicle to supply a secondary source of power if needed e.g. at night and sell excess to the grid[550].

Peak demand generally occurs between 5 p.m. and 11 p.m. for most grids globally. This is the time when most private and public vehicles are parked at homes or parking stations. At this period, the vehicle to house (V2H) technology will enable the parked vehicles to supply electricity to home to meet demand peak demand while any excess can be exported to the grid. The car can also be charged using solar energy like rooftop solar PV. The V2G technology can be applied by having electric vehicles clustered via an aggregator to offer grid power services like voltage regulation, load leveling, and peak shaving, at a lower cost and with less environmental impact which makes the smart grid technology ideal for deployment of V2G and hence play an important role in the energy transition[3, 56, 96].

The communication between the grid and electric vehicles facilitates sharing and exchange of information with respect to the state of charge of electric vehicles, availability of recharging stations and user data. Electric vehicles are in most of the time in a state of rest in the garages of the houses or in the parking lots, hence they can be easily charged by the G2V system and be later used as a source of charge for the grid. The communication between electric vehicles and smart grid takes place in V2G discharge mode, from the vehicle to the grid, with the vehicle as source of distributed generation and G2V which is charging mode. Drivers benefit from the use of electric vehicles since electricity is cheaper than petroleum power. The electric vehicles also provide income to vehicle owners by selling power to the grid [549].

16.3.15. Results and Discussion

In this study current trends and application of the smart grid is enunciated. The electricity grid has to continuously and consistently progress so that it can meet the growing needs in electricity sector and to replace old-pattern power generation with renewable generation with electricity provisions from green energy resources[29, 65, 96]. The smart grid is modernizing power systems towards high consistency, higher efficiency, reduction in costs and power losses while incorporating variable renewable energy sources to the grid. The electricity market is characterized by changing consumer needs and trends, new industrial invention and growing demand for renewable energy resources for power generation[61]. These changes and advances in the electricity and general energy markets call for modernization of the electricity to cope with the changing markets. The. Smart grid has

emerged as an ultimate answer to the ongoing technological and electricity market reforms occurring in power generation, the transmission and distribution that requires increased application of sensors, advanced two-way communication computers [21, 65].

The Smart Grid system is a complex and multi-disciplinary, and relatively under-researched concept. Smart grids implement smart contracts which are integrated with smart energy meters hence allowing tracking of energy profiles against available energy flexibility transactions as well as decentralized settlement of participant wallets[568]. The study demonstrated the significance of block chain and smart contract technology which is growing rapidly with many companies and industries adopting the technology. The adoption of block chain and smart contract technology will bring significant benefits to both consumers and prosumer in a decentralized a smart grid[1008].

The use of smart grids can enable up to 100% uptake of renewable energy in the local micro-grids. When used in micro grid application, smart grids can make it possible to realize up to net [100]zero the exchange between a local micro grid and utility grid even when we have high variability and intermittence of the renewable sources of energy particularly wind and solar.

By facilitating efficient monitoring and feedback between consumers, producers, the utility and other stakeholders within the grid system, energy costs and unnecessary consumption and overloads can be avoided and achieve energy balance at micro grid as a benefit of enhanced monitoring of energy flows, electricity demand and power generation, power generation enabling a high level of energy flexibility[74, 140]. Through provision of optimizing capacity, use of smart grids facilitates cost reduction of the cost of energy or electricity.

16.4. Technologies in Smart Grids

Smart grids make use of a broad range of technologies and appliances. They include smart meters, SCADA, and FACTS while several technologies are still in early stages of development like PMU, and V2G technologies. Of the technologies used in smart grids, some are specific to electricity systems, while others cut across other energy systems, but others are common information and communication technology applications in other sectors. The various technologies in smart grids are summarized in Table 16-1.

Table 16-1: Technologies in smart grids

	Area of Technology	Hardware	Systems and software	Network deployment
1	Wide area monitoring and control	Phasor measurement units (PMU) and other sensor equipment	Supervisory control and data acquisition (SCADA), wide-area monitoring systems (WAMS), wide area adaptive protection, control, and automation (WAAPCA) and wide-area situational awareness (WASA)	Transmission
2	Information and communication technology integration and office computers	Communication equipment (power line carrier, WiMAX, LTE, RF mesh network, cellular), routers, relays, switches gateway, computers (servers)	Enterprise resource planning software, customer information system	Transmission and distribution
3	renewable, distributed and conventional generation integration	Power conditioning equipment for bulk power and grid support, communication and control hardware for generation and enabling storage technology	Energy management system (EMS), Distribution management system (DMS), Supervisory control and data acquisition system (SCADA), geographic Information system (GIS)	Transmission and distribution

4	transmission enhancement	Superconductors, Flexible alternating current transmission system (FACTS), High voltage direct current transmission system (HVDC)	Network stability analysis, automatic recovery systems	Transmission
5	Distribution grid management distributed energy resources	Automated re-closers, switches, and capacitors, remote-controlled distributed generation and storage, transformer sensors, wire and cable sensors	GIS, DMS, outage management system (OMS), workforce management system (WMS)	Distribution
6	Advanced metering infrastructure (Smart metering)	Smart meter, in-home displays, servers, relays	Meter data management system (MDMS)	Distribution and (transmission)
7	Electric transportation charging	Charging infrastructure, batteries, inverters	Energy billing, smart charging grid-to-vehicle (G2V) and discharging vehicle to-grid (V2G) methodologies	Distribution
8	Customer-side systems and demand response	Smart appliances, routers, in-home display, building automation systems, thermal	Energy dashboards, energy management systems, energy applications for smart	Distribution and (transmission)

accumulators, smart thermostat	phones and tablets

From Table 16-1, it is noted that smart grids function because of the various technologies cutting across power, electronics, communication, and computer technology.

The smart grids incorporates technologies that facilitate real time monitoring and control of power making it possible for grid operators to introduce different tariff structures that enable demand side response and management[618]. Power consumers are also provided with trading or business opportunities created by decentralization of generation through energy savings and revenue by trading over smart grid block chain-driven decentralization and flexibility made possible by digitalization like smart metering and use of flexibility tokens. Consumers can generate for self-consumption when prices are high and sell excess when prices are favorable in a two-way trading over the smart grid. Figure 16-1 shows diagrammatically the various functions of a smart grid[3, 61].

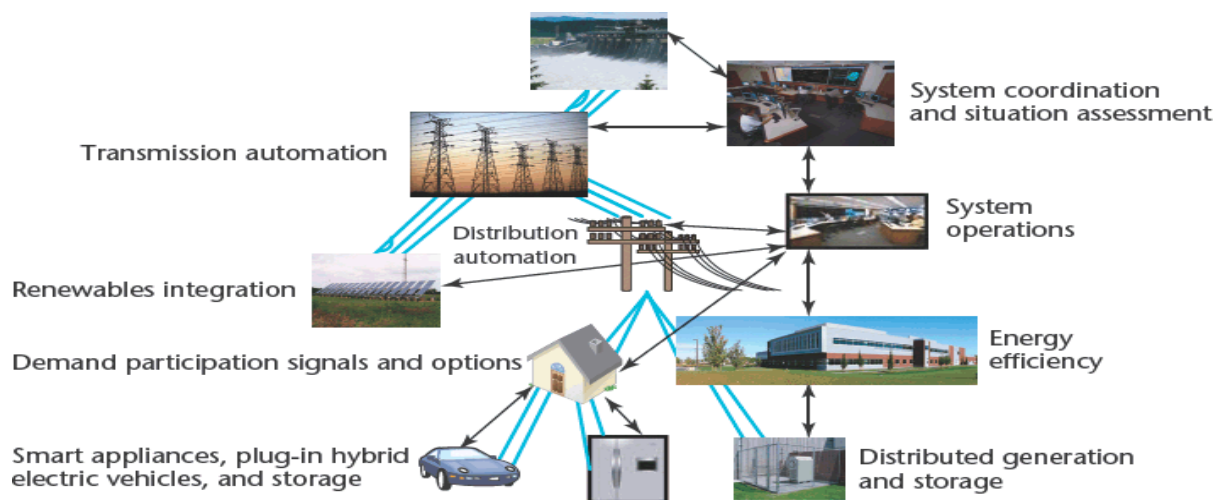


Figure 16-1: The main functions of the smart grid

From Figure 16-1, the main functions of smart grids are summarized as integration of renewable energy, smart appliances, distributed generation and related storage, electric car charging infrastructure as well as V2G facilities, transmission, and distribution automation functions, energy efficiency improvement among others.

Although smart Grids provide better efficiency in monitoring power consumption, manage peak demand by directing power supply to manage peak power needs and enhance efficiency in transmission and distribution, they open an opportunity for information security breaches

and other types of security related risks like meter manipulation, high-impact attacks on critical infrastructure that can lead to grid failure[61].

16.5. Smart Grid Architecture Versus Conventional Power Systems

The key domains of power systems are power generation, transmission, and distribution while the main elements of the traditional power generation scheme are a synchronous generator in a 3-phase electrical energy generated in centralized power stations. On the other hand, distributed energy systems are interfaced with power electronic devices needed to meet varying load requirements of users[1009].

For smart grids, there is need for a communication layer to interoperate between manual control and multiple sensors, automatic controllers, and actuators in the physical layer of the grid. Communication in electricity systems ought to be robust to meet the latency and overcome the bandwidth challenges. Commonly used communication technologies are IEEE specified Zigbee, WiMAX and wireless LAN technologies, GSM 3G/4G cellular and DASH7[1009]. The power line communication (PLC) is the most common standard communication in power systems and smart grids applied low, medium and high voltage electricity networks. Smart grids need a robust communication network for successful operation of wireless sensor networks (WSNs). Data exchange and storage for smart grid protection and control applications is facilitated by the information layer of smart grid. The smart grid automation architecture can be provided by standards - IEC 61850 and IEC 61499 which support multi-agent intelligence and distributed automation simulation while software like SimPowerSystems in Matlab can be applied to validate custom-designed user datagram protocol (UDP) socket. Market algorithms can be applied to maintain a balance between demand and supply where in some typical applications use Power Matcher software is applied[1009]. Application of multiple gateways at customer levels can define security architecture that provides communication and cryptographic abilities amongst themselves and external entities whose benefit is to preserve privacy in the network. Homomorphic encryption can be used for demand response schemes [1009].

The main components of the smart grid architecture are summarized in Table 16-2.

Table 16-2: Summary of architecture [985]

Element s	Construction	Applications

1	Supervisory Control and Data Acquisition System (SCADA)	This is an Extra High Voltage (EHV) transmission network (110kV and above) that is traditionally smart or intelligent equipped with automation and real-time communication systems for system operations.	SCADA operates by collecting information related to grid operation from various sensors located at various points and sending data to the master computer for real time analysis. SCADA with the EMS monitor and control of power flows in real time at dispatch centers or at load control centers of Extra High Voltage (EHV).
2	The Energy Management System	Energy Management System (EMS) is used by grid operators as a tool for monitoring, controlling and optimization of power generation and transmission systems. It facilitates real time network and contingency analysis.	The EMS enables real-time functions which enable the plant operator to monitor, analyze and control power generation functions on a real time basis. It enables automatic generation control, sets economic dispatch, and directs the dispatcher to set economic base point for the generator units selected, monitoring of the reserve, and establishing spinning reserve, regulating reserve and operating reserve levels.
3	Wide Area Monitoring System (WAMS)	The system deploys Phasor Measurement Units (PMU) used for faster and more accurate measurement of the grid equipment. Additionally, SCADA data does not have timestamps, while PMU data is accurate time stamped. Operationally SCADA works like an X-Ray, but PMU Data is like	This requires a fast communication system to handle these huge amounts of data from the phasor measurement Units (PMUs). For real-time wide area monitoring applications, the latency requirements are high in the range of 100 milliseconds to 5 seconds. The main differences in functionalities between PMUs and SCADA is that in SCADA data is collected in 1-5 seconds, but PMU data is captured in

		an MRI scan of the electricity grid	milliseconds.
4	Distribution automation (DA)	The DA involves computerized control strategies used to upgrade implementation of energy dispersion. The lattice physically recognizes and breaks down the energy system physically and remotely enacts gadgets or dispatch an expert to intervene.	The distribution automation (DA) enables specific gadgets to detect operational states of surrounding lattice then influence necessary changes to streamline operation making the network more proficient and solid. The DA facilitates change of controls to suit fluctuation, control inclining and bi-directional power streams.
5	Substation Automation and substation automation systems	Through automation of substations, the equipment or components of substations are made digital (or numeric) with related communication systems to facilitate remote operation.	Substation automation cuts down interruptions and downtime caused by equipment failures, strikes from lightning, accidents and natural catastrophes, surges or power disturbances and substation outages. Substations automation enables the utility company to remotely monitor, control, coordinate and operate power distribution components at substations
6	Advanced metering infrastructure (AMI) or Smart Metering system	comprises of equipment or devices like Smart Meters, Data Concentrator Units (DCUs) also referred to as gateways, routers or access points, Meter Data Management System (MDMS), Home Area Network (HAN), Head End	The smart meter electronically records electricity consumption normally on hourly intervals or less and communicates with the utility on regular basis for monitoring and billing. They facilitate a two-way communication between computer systems/computers at the utility control centers and the meter the

		System (HES).	consumer point
7	Block Chain Technology infrastructure	The block chain technology is made up of distributed information and communication technology	It supports decentralized structure of local energy markets and facilitate direct interaction between smart grid users

From Table 16-2, it is noted that the main elements of the smart grid architecture and operations are the Supervisory Control and Data Acquisition System (SCADA), Block Chain Technology infrastructure, Advanced metering infrastructure (AMI) also called Smart Metering system, Distribution automation (DA), Substation Automation, Wide Area Monitoring System (WAMS) and the energy management system (EMS). Other components of the smart grid architecture are household appliances, energy sources, Smart Meters, the Power Utility Centers. The smart meter contains a microcontroller that has memory, digital ports, timers, real-time, and serial two-way communication facilities. Smart meters join house or user devices and the external systems to the utility monitoring and control systems.

16.5.1.Characteristics of Smart Grids

Smart grids integrate electricity networks consisting of transmission and distribution systems and interfaces with generation, storage, and end-users. The smart grids are evolving set of modern technology that can be deployed globally guided by local commercial attractiveness, legal and regulatory framework, technology compatibility and investment frameworks[70, 1010]. The main characteristics of smart grids which influence their application are as follows.

- i. Smart grids have ability to integrate different energy sources in the distributed energy system in a way that optimizes power and delivered effectively to the grid [1011, 1012].
- ii. The smart grid system facilitate quick electricity demand response (DR) that can create peak load sharing, load profile shaping with high degree of effective and reliable control and maintenance [67]. Which effectively increases the utility and control of distribution system equipment, improves demand response, leading to better power system stability [1010].

- iii. The system applies communication systems like wireless, wired communication technologies and end to end communication management to provide integrated communication system through Distributed Automations System (DAS) and other technologies. [1012, 1013], to coordinate and integrate communication, new metering, system controls, and customer engagement technologies and strategies, by leveraging technologies and programs to realize across the entire power utility system [95].
- iv. The smart grid system uses Advanced Metering Infrastructure (AMI) for communication between the utility company, consumers and operators [312]. Individual equipment and customers are metered throughout the distribution system as well as transformers, switches, capacitor banks, voltage regulators and other equipment. Information from these equipment and customers is relayed to the utility in a typical two way communication [1010].
- v. Applies cyber secured communication like data supervisory control and Energy Management System[106, 1013].
- vi. The smart grid enables demand profile shaping, and peak load shaving to optimize power generation cost and increase consumer utility through real time pricing technologies [1013].
- vii. The smart grids facilitate greenhouse gas emission minimization by efficient integration of variable renewable energy sources and variable loads like electric cars compared to the conventional grid system [103, 1013].
- viii. Enables active participation of stakeholders like the customer which enables customers to provide electricity and additionally respond actively to signals from the utility meant to reduce electricity during peak hours and during times of distress for the utility[1010].
- ix. The smart grid has infrastructure to support a two was communication as well as flow of electricity from to and from the utility to the customers which converts electricity consumers to prosumers [70]

16.5.2. Conventional verse Smart Grids

The main differences between smart grids and convention grids are summarized in Table 16-3.

Table 16-3: Differences between conventional grids and smart grids

	Basis	Conventional grids	Smart grids
1	Communication	One way communication	Two-way communication
2	Power generation	Centralized power generation	Distributed and central power generation
3	Network connection	Radial network	Interconnected network
4	Sensors	Uses basic sensors	Uses Multiple advanced sensors
5	Mode of operation	Manual or analogue operation	Digital operation
6	Control and monitoring	Limited manual monitoring and control	Wide range Automatic monitoring and control
7	Security and privacy	Limited security and privacy concerns	Serious security and privacy issues

From Table 16-3, it is noted that there are significant differences between the smart grid and the conventional grid. The smart grid is equipped with automatic monitoring and control capabilities making it a complex intelligent system.

16.5.3.Stakeholders in Smart Grids

The smart grid system is composed of many organizations that cumulatively constitute a recognized area of institutional life. The smart grid operating environment has got several stakeholders who are interrelated. As per the Smart Grid Interoperability Panel (SGIP) and National Institute for Standards and Technology (NIST) algorithm or methodology which is used for planning or organizing the various smart grid networks interconnections, there are 7 domains of the smart grid that represent the 7 main stakeholders. They are; service providers, generation, customers, transmission, , distribution, the operator and the market[559].

The stakeholders and their role in a smart grid system are summarized below[97]. Table 16-4 is a summary of the various smart grid stakeholders and their functional roles.

Table 16-4: Stakeholders and role in the smart grid system

	Stakeholder	Role
1	Customers	Electricity is consumed by consumers. It may be domestic, commercial, or industrial
2	Operations	Operations related to power systems are performed. It comprises of regulatory authorities or management responsible for movement of electricity
3	Markets	Grid assets are used by stakeholders. Both operators and consumers are playing role as market.
4	Generations	Electricity is generated. Generation companies in bulk quantity of electricity are involved as player.
5	Transmissions	Electricity is transmitted. Companies or player responsible for transmission of generated electricity for distribution.
6	Distributions	Electricity is distributed to end consumers and monitored. They include distributor of electricity form and to customers.
7	Service providers	They provide support services to all the power system stakeholders like internet and communication services. providers

Table 16-4 summarizes the main stakeholders in the smart grid system namely, markets, customers, generations or power plants, transmission, distributions, and various service providers together with their functions in the smart grid system. The positional relationship between smart grid stakeholders is presented in Figure 16-2.

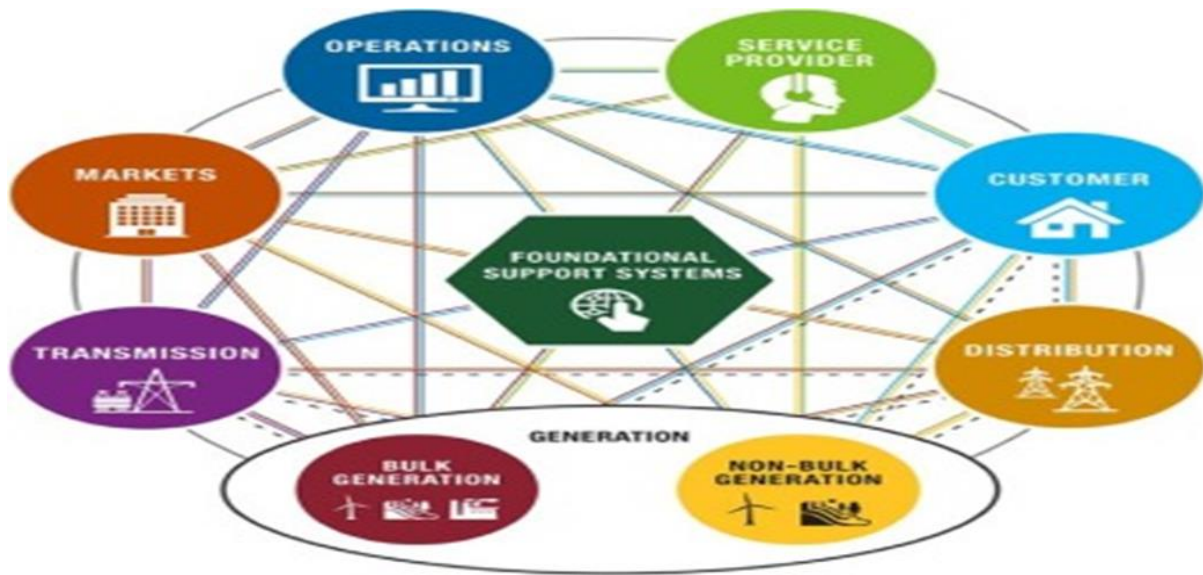


Figure 16-2: The positional relationship between smart grid stakeholders

16.5.4. Benefits of Smart Grids

Smart grid (SG) facilitate power generation decentralization and intelligent management of generation, transmission and distribution resources. A smart grid is an electricity network allowing devices to communicate between suppliers to consumers, allowing them to manage demand, protect the distribution network, save energy, and reduce cost. The system has demonstrated ability and competence to meet required electricity availability, supply reliability, power quality, as well as economic and efficient operation, enhanced safety, higher security, and enhanced solution to the challenge of global greenhouse emissions and global warming and hence a better environment and sustainable future[618]. By investing in smart grids, provides an opportunity to maximize the return on investment (ROI) by using Smart grids to analyze important data and automate finding operations which can increase revenue and minimize expenditure [61].

There are several specific benefits for the use of smart grids. According [564]. The benefits of smart grids are.

- i. The smart grid system enables seamless connection and operation of different generators in terms of size and technologies.
- ii. Reduces maintenance expenditure through automatic reporting and tracking as opposed to manual or physical tracking which is expensive and inefficient.

- iii. The use of smart grids reduces electricity theft through remote monitoring of meters and any tempering attempt raises an alert signal. Utilities are also immediately notified if deviations in power consumption are noted prompting swift action.
- iv. They enable automatic load balancing which reduces the risks of equipment failures as opposed to manual adjustments. Smart grids rely on genetic algorithms to review consumption patterns and manage loads which reduces stress on electrical equipment, especially during peak times.
- v. The smart grids enable higher power transmission efficiency since they have ability to regulate electrical transmissions by relying on intelligent technologies to mitigate electrical losses in distribution which improves efficiency of electrical transmission, for the benefit of all stakeholders.
- vi. Smart grids improve power system stability, security, significantly.
- vii. Smart grids prevent transmission oscillations, overload, and resultant blackouts by facilitating automatic loading and re-routing of electricity any time an equipment fails.
- viii. Smart grids help consumers to save on energy cost by providing time information on demand and price to enable them to plan their consumption.
- ix. Smart grids facilitate better integration of renewable energy by enabling accurate planning through timely data on both weather and demand as well as increased flexibility which enables the great to absorb more variable sources of power and loads.
- x. Better facilitate the connection and operation of generators of all sizes and technologies seamlessly to a common platform.
- xi. Smart grids optimize grid operation which improves overall reliability and stability of the power system by allowing consumers to be active participant in the optimization of the grid.
- xii. Smart grids facilitate accurate and timely planning and action by availing real time data and information to create a stable, efficient, and cost-effective system.
- xiii. The use of smart grids facilitates reduction in the environmental impact of power systems through optimum loading of generation systems.
- xiv. Improves reliability, quality, and security of the electricity supply system.
- xv. Smart grids help improve the quality and performance of energy products and services by fostering market integration and harmonious stakeholder relationship and operation.

- xvi. Smart grids convert electricity consumers to prosumers who do both generation and supply of grid power based on variable pricing and two-way flow of electricity and data.
- xvii. By combining or integrating weather and demand forecasts, more accurate generation planning, and dispatch can be done.
- xviii. They provide resilience to system attacks, and disaster in terms of enhanced ability to react to emergencies by isolating and re-routing power flow including self-healing ability which reduces downtime and outages.

The smart grid system offers solutions to several challenges facing power generation, transmission, distribution, and power system control by providing necessary capacity and infrastructure to enable efficient use of variable renewables and variable loads while at the same time guarantee a stable and reliable power supply and minimize fossil fuels. Through these functions and capabilities, the smart grids provide an avenue for sustainable electricity generation and supply as can be summarized in Figure 16-3.

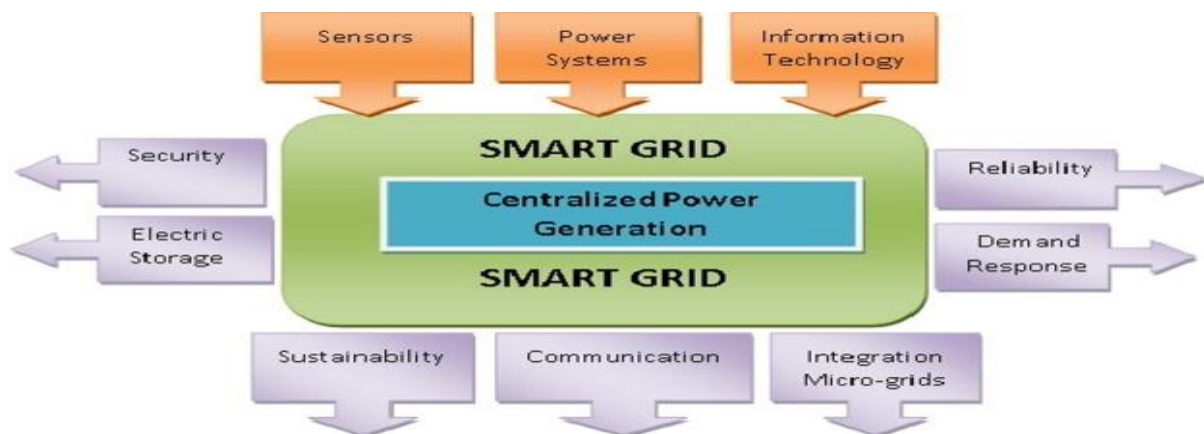


Figure 16-3: Smart grid environment and impact on sustainability

From Figure 16-3, it is observed that the smart grid provides a conducive environment that will facilitate sustainable energy and electricity transition through features and technologies like the sensors, information system, power electronics, communication, energy security, storage infrastructure, demand response capability and facilities, and seamless coordination of a mix of central and decentralized power generation and distribution.

16.5.5. Summary of Features and Capability of Smart Grids

The smart grid system has several capabilities that enable it to function. These capabilities are summarized in Table 16-5.

Table 16-5: Capabilities and benefits of smart grids [97]

	Capability/function	Sustainability impact
1	Seamless connection of generators of different sizes, features, sources of energy	Prevents power loss and maximizes use of variable loads and power sources
2	Enhances reliability, security, and stability of supply	Guarantees sustainable electricity supply
3	Enable automatic loading and re-routing of electricity whenever equipment fails	Avoids unnecessary power supply losses and reduces downtime hence high supply security and reliability.
4	Prevent transmission oscillations and overload which often cause blackouts	Reliability of power supply and more absorption of variable loads like electric cars and variable supply like wind and solar power.
5	They provide real-time information on consumption to stakeholders.	Facilitates social sustainability and technology acceptance which is a sustainability requirement.
6	Enable consumers to adjust in time and quantity of energy usage	This will reduce overload on generation facilities, improve efficiency and hence avoid wasteful generation and consumption.
7	Facilitate higher integration of renewable energy	Facilitates fossil fuel substitution in power generation.
8	Convert consumers to prosumers who produce and sell their own	Provides a revenue source for consumers, motivation to consume less and generate more and enable economic sustainability of power systems.

9	Optimize overall grid operations from generation to consumption.	This will reduce wastes and pollution, avoid unnecessary generation and consumption as well as avoid unnecessary investment and costs in the power system.

From Table 16-5 it is observed that the smart grid has several capabilities like ability to seamlessly integrate variable renewables and optimize grid operations which gives it a significant role to place in the energy transition from fossil fuel based to low carbon and renewable energy resources.

16.6. Applications of Smart grids

Energy sustainability and transformation is a global challenge which faces issues like wide demand supply gap, overreliance on fossil fuels, and low penetration of variable renewables. The smart grid has been identified as a potential solution in the smooth transition from traditional to modern smart energy systems [56]. They facilitate integration of all forms of electricity generation across the in the grid coverage. Smart grids can be used to optimize energy consumption because of their ability to integrate sources, direct and coordinate operations. throughout the entire energy supply chain. Smart grids can enable electricity consumers to realize financial savings and income through measures like flattening peaks and conversion of consumers to prosumers who not only consume power but also supply power in a two-way power flow process in a smart grid[3, 21, 61]. As a result, smart grids offer opportunities for new, energy-related services while making energy systems more dynamic and improving security of electricity supply. Therefore, smart grids have an important role to play in the global energy transition to renewable and low carbon energy sources [12, 61, 98].

There are various applications and features of smart grids which significantly make them superior compared to the traditional grid. These are summarized in Table 16-6.

Table 16-6: Applications of smart grids

	Function	Application	Impact
1	NET metering	Electricity imports and export	Turns consumers of electricity to prosumers who are keen to be net exporters not importers
2	Time of Use	Enables variable pricing of	Facilitates demand side management

	(TOU) Metering	power	by demand shifting
3	Peak load shaving	Demand shifting which reduces maximum demand and cost.	Smart grids create flexibility and demand shifting leading to load management, peak shaving and energy saving by moving to off peak hours. The Peak load benefits all consumers and the utility operators by avoiding overloading of the system
4	Power quality improvement	Reliability and quality improvement. SGs are equipped with automatic power factor correction devices and modern communication functions for regular reporting to the utility control center	The grid intelligence, resilience, flexibility, and adaptability are enhanced by use of smart grids. Smart grids use automatic power factor correction (APFC) devices and active filters to improve the power factor and power quality.
5	Outage Management through self-healing and early detection	SG are equipped with Outage management system (OMS). The DTMS systems is equipped with oil sensors, palm sensors, CT and PT. which enable Distributed Transformer Monitoring System to detect and correct faults	The outage management system enhances the reliability of the power systems by application of the grid smartness for operational benefits like power restoration, reliable and cost-effective services with less manpower and hence costs
6	Loss detection which ensures timely action and low outage	Smart meters collect, compute, store, and transfer energy data to control centre at constant intervals. Power losses can be determined by comparing the energy data at different nodes and DT terminals	This enables quick measures to restore power to consumers immediately power loss is identified.
7	Improves	This is achieved in Smart Grid	Facilitates efficient monitoring of

	power system reliability	by the ability to detect faults and self-healing potential of the system. SG can monitor all information and data and can establish system reliability. Smart grids make use of technologies like Dynamic Stochastic Optimal Power Flow (DSOPF) which make it possible to estimate and optimize	hybrid generation and management of the grid remotely which improves power reliability. power flow in the system. Therefore, Smart Grids can improve system reliability through enhanced metering and communication
8	Demand Side Management through participation of consumers	Demand response is the ability by consumers to modify energy consuming models in response to variations made possible by the two-way communication ability of smart grids.	Enable a more economical use of grid power and hence higher efficiency and reduced peak time stress by shifting load and self-generation. Demand response enables the distribution system to schedule resources based on requirement. The system also provides financial incentives by scheduling consumer needs.
9	Decentralised power generation.	Decentralized generation uses different local energy sources to meet the demand of local electricity demand by integrating various forms of locally available supplies including energy storage.	Leads to more use of renewable sources and hence emissions. Distributed generation also helps to address twin challenges of generation fluctuations and huge land requirements associated with wind and solar energy resources
10	Micro grids which are more resilient	Micro grids are small and autonomous subsets of the main electricity grid, which help reinforce the self-healing characteristics of smart grids	Micro grids supply energy obtained by means of distributed energy resources (DERs) to nearby consumers. Smart grid components can be used to fix issues facing

		and support decentralized generation	traditional micro grids thus transforming them into smart micro grids by introducing smart technologies
11	Integration of Renewable Resources	Substitution of fossil fuel sources	More reliance on local resources hence more energy security
12	Internet of things (IoT)	The internet of things enables access to information any time wherever you are connecting devices through real-time information	Helps to achieve optimal control and maintenance of home appliances by integrating recent and modern Information and Communication technologies (ICT) and energy technologies in the housing environment. These reduces energy cost and wasteful use of energy.
14	Smart charging Electrification of transport hence reduced emissions	Electric vehicles use chemical energy stored batteries that can be recharged and used in vehicle propulsion and supply of power to the grid when prices are favourable. Reduces emissions from transport sector which is about 14% of global GHG emissions from anthropogenic sources.	Smart charging can be centrally done through aggregators or can be decentralized using decentralized control structures. Smart charging using both centralized and decentralized systems can effectively reduce energy costs and prevent the overloading of grid components by shifting peak demand.
15	Reduce Transmission & Distribution Losses hence high efficiency	Decentralization of generation at sites close to consumers hence less transmission and distribution costs and losses.	Increased use of decentralised resources increases energy security and more use of renewable sources in power generation, increases access and reduces cost of power.

17	Development of smart cities and streetlight automation	Smartness of a city refers to the desire to improve the quality of life in a city and living standards of the city residents in terms (ICT). Intelligent application of smart grid is a key requirement for the establishment of smart cities.	Smart cities have been identified as the ultimate solution to complex challenges facing urban centers like energy supply, emissions, water supply, traffic congestion. Cities will account for about 70% of global population by 2050.
18	Grid Integrated Energy Storage	Seamless integration of energy storage to the grid	Optimum use of energy storage leading to increased uptake of variable renewable sources of energy.
19	V2X technologies	Smart grids will enhance electrification of transport creating opportunities for related sustainable technologies like V2V, V2H, V2G	Therefore, smart grid technology deployment will enhance the operation and control of electric vehicles making them important energy transition facility
20	Rural electrification	The smart grid also provides significant opportunities for alleviation of rural electrification through development of smart micro grids based on renewable energy sources	Through smart grids, significant opportunities for alleviation of rural electrification challenges are addressed by providing infrastructure for wider exploitation of renewable energy sources like biomass, solar PV, and wind, through active engagement of individuals, private business and connecting them to the national grid

Table 16-6 summarizes the various applications of smart grids which improve the sustainability of grid electricity. This is realized by increasing system efficiency, increased uptake of renewable sources of energy, increased energy security by enhanced decentralized generation utilizing local energy resources. By two-way communication and flow of power,

consumers are converted to prosumers. Improved stakeholder interaction due to active participation using two-way communication increases social sustainability of energy systems.

Smart grids use semiconductor-based FACTS and RACDS devices, replace mechanically driven devices making the grid responsive in case of faults and reduces electricity losses. The smart grid also provides significant opportunities for alleviation of rural electrification through development of micro grids based on renewable energy sources like biomass, solar PV, and wind, through active engagement of individuals, private business and connecting them to the national grid[56]. Additionally, through scheduled charging of electric vehicles, the smart grid will encourage people to embrace EV technology leading to emissions from the transport sector and significant reduction in dependence on fossil fuel and transforming the transport sector into a partaker in demand response management [56, 61].

The Smart Grid functionality has a very critical role in the delivery of electricity to consumers in a participatory manner by many players[562, 1014]. These are achieved through the following function.

16.6.1. Monitoring of Distribution Grids

The primary objective of smart grids is to increase the transparency in the operation of the distribution grid through improvement in the monitoring capabilities. According to [1014] the traditional grid needs extra technologies in the distribution domain that are required for deployment of smart grids. They include Automated re-closers, switches, remote controlled distributed generation and energy storage, sensors for cables and cables and transformer. The sensors needed can be dedicated grid sensors especially for transformer substations and at critical locations within the network. Smart energy meters can also be used to reveal essential data for grid operation, control, and planning. The smart grid ICT has the main duty of transporting grid monitoring data across the power grid [562].

16.6.2. Provision of Ancillary Services for Users

Ancillary service are services provided by power network participants particularly the large power plants required for safe and reliable operation of the power system. These services include frequency control, reactive power control, and voltage regulation . With smart grids, significant generation is shifting to the distribution grids hence connected generators will increasingly be involved in provision of the ancillary services. Additionally, the power customers will also provide ancillary services in the form of active management of load flexibility. Virtual Power Plants or aggregators can combine small units of generators, loads,

storages and generate ancillary services from their resources which increases power system reliability and efficiency. The communication and management between individual units and the aggregators and ancillary service providers to consumers is another important application for smart grid information and communication technology (ICT) [562, 1014].

16.6.3. Advanced Control of Distribution Grids

Technical barriers to grid integration of variable renewable energy sources have been a major driver for smart grid deployment. The main technical barrier is increase in line voltage levels from distributed generators[562]. The approaches used to solve the problem are.

- i. Grid reinforcement involves building of new lines or transformer stations, an option which is considered expensive and economically to solve voltage problems although it may be ideal for line overloads.
- ii. Transformer or line-based techniques where components like on-load tap changers or alternative continuous techniques are applied to change the voltage on a particular line. This consists of hardware components like a transformer with switchable windings and an associated control algorithm. The hardware components are currently available as products today e.g., in medium voltage level, and at low voltage level. However, the control algorithms are still under research and development. Today, the products like “intelligent secondary transformers are equipped with simple controllers based on local measurements [562, 1014].
- iii. Generator-based techniques: In these techniques, the unit causing rise in voltage is also used to keep this rise within limits through reactive power (Q) management or by shedding of active power (P) as last resort. Modern photovoltaic inverters are equipped with selectable $P(U)$, $Q(U)$, $Q(P)$ and $\cos\phi(U)$ characteristics which are controlled based on local parameters in the inverter. The parameters can also be remote controlled for some products although we are yet to have a widely accepted standardized way to realize this end [562, 1015].

16.7. Challenges Facing Smart Grid Power Systems and Technologies

Smart grids can deal with many current issues with the traditional grid by application of cutting-edge technology with a plethora of chances to improve efficiency and reliability of power systems. However, several socioeconomic and technical can hinder their deployment and applications[71]. Since the grid is a complex architecture, decentralization by use of smart grids brings tremendous benefits at a cost. However, digitalization and integration of a

large number of growing users makes smart grids soft targets for cyber-attacks and breach of confidentiality among other limitations[562]. Smart grid technologies, although promising, have several challenges as summarized in Table 16-7.

Table 16-7: Challenges facing smart grids.

Challenge	Causes and Impact	Solution/Recommendations
1 Cost challenges	The main cost elements in smart grid development are associated with the power transmission and distribution system, electricity metering, and critical technologies. In economic analysis and financial feasibility	A country's capacity to pay for the development cost for smart grid infrastructure is paramount which disadvantages developing countries. `Funding by international institutions can facilitate access to requisite funding for smart grids.
2 Cyber Security	Smart grids deployment across the value chain, increases points of interconnection with different information networks which exposes the system to threats of cyber-attack to important power management systems and infrastructure.	Cyber security can be achieved through standardization. It is necessary to identify weaknesses of the smart grids exploited by attackers through Smart Grid Systems Treats Analysis and by integration of Systems Security Threat Models
3 Interoperability	Interoperability facilitates connection of different parties to the devices and systems for proper interaction	The interoperability can be achieved through strict implementation relevant standards

4	Physical Security	There is risk to valuable assets and systems that are widely spread across the country of power system boundaries	Investment in facility security and proper sitting away from danger and keeping of intruders and risks through access control.
5	Privacy and Security Policies	Wide scale interconnectivity and system access including the growth of Internet of Things associated with smart grid development, privacy, and development rises privacy and confidentiality concerns.	Put in place security policies to establish relationships between the consumers, utilities, generating companies, transmission firms, and third parties, although applying security and privacy policies
6	Connectivity	Refers to communications connectivity and interchange within the smart grid infrastructure and between users or stakeholders.	It is necessary to develop internet and communications infrastructure across the whole power system coverage area.
7	Confidentiality challenges	Access Control and Identity Management is needed for confidentiality of data transmitted via smart grids.	Only authenticated users should be allowed access to the control centre for transmission, and distribution grids
8	Defence	The smart grids have inherent vulnerabilities against which it must be protected. This can be achieved by building an effective, layered defence system for protection of the smart grid infrastructure.	This defence or protection against the threats or vulnerabilities give the network segmentation and access control to defend against denial-of-service (DoS). Technologies used include firewall, virtual private network (VPN),

intrusion prevention system (IPS).

From Table 16-7, challenges facing smart grids include high cost of investment and limited access especially for developing countries having multiple socioeconomic challenges, interoperability of standardization related issues, cyber and physical security, communication and internet connectivity challenges and high system security requirements.

16.8. Role of Smart Grids in the Sustainable Energy Transition

Smart grids have an important role to play in the sustainable energy and electricity transition within the framework of the 5 dimensions of energy sustainability. They are summarized in the Table 16-8.

Table 16-8: Role of smart grids in the energy transition and related challenges

	Dimension of sustainability	Sustainability impact	Challenges
1	Economic sustainability	Converts consumers to prosumers who make revenue and save on cost through variable pricing.	▪ It is difficult to understand and communicate the value proposition of a smart grid deployment for all stakeholders in the power system. ▪ The risk and reward system can challenge business plans for smart grid investments. ▪ Regulatory environment or lack of regulation may create challenges in terms of costs and related expenditures. ▪ It is difficult to develop and implement an appropriate incentive structure aligning economic and regulatory policies with energy-efficiency and environmental goals.

			▪ Smart grid infrastructure is expensive to deploy and requires highly trained personnel.
2	Environmental sustainability	Reduces greenhouse gas emission through higher absorption of variable renewables. As well as high efficiency hence less consumption	The level of emissions reduction is highly dependent on the energy mix. Not all areas are endowed with abundant supply of solar and wind resources to exploit decentralized power generation.
3	Social sustainability	Maximum use of local energy resources, employment and cleaner environment and participatory operations	▪ Valuation of smart system externalities is difficult making balanced decision making. ▪ Smart grid technology deployment and implementation requires highly skilled manpower hence high staff development cost and time. ▪ It is difficult to value the value of benefits to the community in terms of jobs and advancement of skills.
4	Technical sustainability	Facilitate micro grids and decentralized generation. Increases reliability, efficiency, and optimum use of all energy resources in the system as well as the infrastructure.	▪ Need for designs to accommodate multiple technologies due to constant technology changes. ▪ Flexibility to changing technologies requires identifying the important interfaces between technology components which may be difficult. ▪ Limited standardization as the industry is still evolving.

5	Institutional sustainability	Facilitates active participation of all stakeholders where all stakeholders benefit.	▪ Develop policies that support the deployment of renewable sources and efficiency in electricity transmission, distribution and consumption which create demand for smart energy systems. ▪ Countries should set up regulatory regimes that encourage investment and deployment of smart grid technology and infrastructure. ▪ There should be an appropriate incentive structure that aligns sustainable energy with smart grid technology.

From Table 16-8, it is noted that smart grid technology still faces sustainability challenges which should be addressed by countries. The table presents the role of smart grids in the sustainable energy transition and their current challenges. Overall, it is noted that whereas smart grids have huge capability or potential to transform power systems, they have several challenges that need to be overcome in all dimensions of sustainability. They include high cost, risks to the infrastructure, volatility of related technology, and huge policy and institutional requirements for sustainable adoption and transformation.

16.9. Conclusions

The Smart grid is a technology of the future whose primary objective is to reduce costly peak demands, maximize absorption of variable renewables and reduce energy related greenhouse gas emissions and facilitates dynamic pricing which enhances consumer awareness and participation in power generation and consumption. Advances in smart grids will add value to electrification of transport making millions of cars not just exist as variable loads but act as renewable energy storage devices and sources of decentralized power for grids. The Smart Grids facilitate increased efficiencies in power consumption usage

monitoring, direct power supplies to serve peak power demand, and enhance efficiency of electricity delivery. Smart grids apply digital technology to avail electricity in the form of an extensive cyber-physical power system which can enable controllability and responsiveness of decentralized electricity generation and supply within the overall power grid system. The Smart grid is the direction and trend of power industry development based on physical grid and that combines advanced information & communication technology with operation technology the traditional grid to form a smart system. The main links covered by the smart grid are power generation, transmission, system transformation, power distribution, electricity consumption and dispatch. The smart grid coordinates the needs and functions of different participants in the grid environment enabling the system to operate on the premise of ensuring system reliability and stability.

The smart grid applies wireless sensor networks (WSNs) communication technologies which are cheaper, faster to deploy, enhances flexibility, and aggregated intelligence via parallel processing capabilities. The internet of Things, which is a characteristic feature of smart grid systems refers to the application of wireless sensor networks (WSNs), smart meters, actuators and components with information and communication technology (ICT) in operations. The main limitation or challenge with integration of the IoT technology within the smart power grid is the introduction of costly large data processing. The data handled within the smart grid system includes end users load demand, faults on power lines, status of network components, scheduling energy consumption, forecast information and conditions, records on advanced metering, outage management records, and records of enterprise assets.

The smart grid is a product of the fourth industrial revolution whose overall result is growth in automation, better communication, self-monitoring, and application of smart machines which have ability to analyze and diagnose issues without with little or no human intervention. The smart grid revolution also represents a social, political, and economic shift from the digital age of the late 1990s and early 2000s to a connectivity embedded era which is distinguished by the omni-use and commonness of technological use throughout society. The fourth industrial revolution technologies have potential to connect billions of people globally to the web and significantly improve the efficiency of doing business globally and improve the standard of living and efficiency in doing many things globally.

Advances in smart grid technology present opportunities to efficiently meet future energy needs by reducing carbon emission and increasing the integration of renewable energy resources in the electricity mix. The technology can improve power system reliability,

quality, and efficiency of power delivery by introducing and facilitating positive consumer behavior in energy use. Significant potential exists for improvement and implementation of smart grid concept which is still under development and adoption and hence the need for government policies and measures to facilitate the implementation of smart grids globally. The capacity of the grid to absorb variable renewable sources of energy is achieved by grid smartening using intelligent systems. These intelligent systems improve reliability, efficiency, and capacity of the grid to deal with variability and intermittence. The use of micro grids as building blocks for smart grids increase access of renewable sources of energy into the mainstream power systems besides increasing efficiency and optimal use of grid facilities through demand response and peak shaving.

There is growing demand for new approaches in electricity grid operation, control, and maintenance for increased uptake of highly variable renewable energy as well as distributed energy resources. Other than variable sources, loads like plug-in electric vehicles and vehicle-to-grid have significant potential for increased if the smart grid infrastructure is available. Therefore, smart grids enable the implementation of strategies to achieve energy and environment sustainability, and climate change control which makes smart grids very useful infrastructure to use in realisation of sustainable energy development. The use of Information Communication and Technology (ICT) in the form of digital and internet technology in electricity networks is a working strategy to realise low-carbon power systems by integration of the fluctuating renewable energy sources, improve conversion or generation efficiency by application of real-time coordination of energy flows, and improved power supply security by means of automatic grid reconfiguration and more active consumer participation in energy markets. The digital technology in power generation and supply within a smart grid system provides an opportunity better economic competitiveness through price competitiveness and high-tech infrastructural modernisation and the attraction and development of high-skilled, well-paying jobs while guaranteeing sustainable energy.

Smart grids will play a very important role in the ongoing transition from centralized power systems to decentralized systems whose control is influenced by dynamic market forces for investment, operational stability and reliability and facilitate greater absorption of variable electricity like solar and wind as well as variable loads like electric vehicle battery recharging system and related products like V2G and G2V. A sustainable electricity mix and power system will require seamless coordination of both centralized and decentralized power generation and distribution. Therefore, to achieve sustainable development requires electricity

systems to adequately respond dynamically, and intelligently to change in demand and supply. This will facilitate energy security, and power quality which are requirements for realization of technical, economic, and environmental performance sustainability. Therefore, smart grids will transform the power sector into a desirable system with reliability, availability, and efficiency, which are requirements for improving the world economy and guarantee environmental protection. However, the transition period requires tests, technological innovations and improvements, consumer education, development of appropriate or requisite standards and regulations, and information sharing or networking between all players in the energy sector to ensure that the benefits of smart grids will be realized globally for all humanity.

The smart grid technology incorporates components of the intelligent energy network system which reciprocate with industry 4.0 namely, Cyber-Physical System, M2M (machine to machine), the Internet of Things (IoT) whose outcome is the application of technology at all levels in the electricity network. Industry 4.0/4 Industrial Revolution and smart grids commonalities include elements of optimization, systems automation, efficient use and management of energy, intelligent decisions, and use of the internet. The overall effect of application industry 4.0 principles in smart grids is better system operation, higher energy efficiency, reduced costs, reduced greenhouse effect, reduced downtime, reduced power losses, improved power quality, effective management of generation and storage systems which are key requirements for the energy transition.

The deployment and optimum use of smart grid infrastructure may require advancement in energy storage technology and facilitating policy, legal and socio-economic environment. The study showed that many components of smart grid systems can be progressively deployed based on new initiatives, policy initiatives, and specific frameworks adopted for implementation by the government or responsible authorities. There exists significant potential of smart grids technology in the entire energy sector that can deliver effective and efficient utilization renewable energy resources, protection of the environment, better energy management, and overall socioeconomic development of all countries. The success of smart grids technology requires that governments and energy sector authorities should put in place policies and frameworks that support and prioritize the investment that promote the use of renewable energy technologies and integration in the entire national electricity grid and all electricity applications.

16.10. Recommendations

The successful adoption of smart grids to make them sustainable option in the energy transition require measures that include.

- i.) Put in place policy measures to develop a common framework for development of smart grid that may be unique to each country for successful deployment of smart grids globally.
- ii.) All stakeholders like consumers, service providers, suppliers, and regulators should play leading roles in shaping the goals and required standards and level of performance.
- iii.) There is need for education and sensitization is on use and benefits of deployment of smart grids to governments and stakeholders.
- iv.) Understanding and communicating the value proposition of a smart grid deployment for each stakeholder in the electricity supply chain is daunting.
- v.) The financial environment for risk and reward can challenge business plans for smart grid investments.
- vi.) Need for development of internationally acceptable quality and operational standards to manage the challenge of interoperability.
- vii.) Governments should put in place necessary regulatory measures to govern the development and operation of smart grids and facilitate harmonious integration and cooperation between all stakeholders. This is because regulatory decisions (or lack of decision) can create new challenges to deployment and operation of smart grids.
- viii.) There is need for the developing an appropriate incentive like attractive fed in tariffs for prosumers and flexibility in pricing that is aligned with requisite economic and regulatory policies where energy-efficiency and environmental protection needs to be the ultimate objective or target.
- ix.) The volatile nature of smart grid related technologies implies that there should be provision for a heterogeneous mix of technology so that existing generation and delivery infrastructure (i.e., legacy) systems can be seamlessly adapted to work with new technologies. To be flexible to technological changes needs the identification of important interfaces between various technology components.

- x.) To realize or achieve alignment across stakeholders like service providers, end-users, and technology suppliers is a challenge which should be addressed by enforcing interoperability can allow multiple parties and devices to interact smoothly and seamlessly. The requires standards and an effective legal and regulatory framework to facilitate a smooth transition and operations.

Wider adoption or development of smart grids requires amendment or development of facilitating legislative and regulatory frameworks for countries still using the traditional grid [1]. There is need to develop incentives for increased adoption of renewable energy technology, measures that promote electrification of transport which is an important user of smart grids like tax measures, workforce capacity building and wider public awareness campaigns to enlighten the public and grid stakeholders to create a mass movement for development and adoption of smart grid technologies and related products and services for sustainable transition [1, 40, 41].

CHAPTER 17:

ENERGY STORAGE IN THE ENERGY TRANSITION

17. Overview

This chapter is a summary of work published in [32, 553] as a book chapter and conference paper. Energy storage systems play an important role in improving the reliability of electricity networks due to increasing share of electricity from intermittent sources like wind and solar. The growing demand for variable renewables has significantly increased demand for energy storage for balancing applications. The main considerations in choosing a suitable storage system are cost and performance. Since the price for every kWh supplied to the network and battery energy storage system (BESS) costs are dynamic, consumers interested in a battery may have challenges in choosing between the various batteries available in the market. This study presents the storage systems and their role in the energy transition. The future power plants are expected to have large proportions of intermittent energy sources like wind, solar or tidal energy that require scale-up of energy storage to match the supply with hourly, daily, and seasonal electricity demand profiles. Available storage technologies include batteries, pumped hydroelectricity storage, compressed air energy storage and power-to-gas storage. The energy transition to renewable energy supply calls for increased application of energy storage. Identification of optimal solutions requires a holistic view of the energy system beyond the electricity-only focus. In this study, an integrated cross-sector approach is adopted to identify the most efficient and least-cost storage options for off grid and grid scale application. Storage batteries can widely be divided into solid state batteries and flow batteries using solid and liquid electrolytes respectively.

17.1. Introduction

Energy storage facilitates temporal and spatial transfer electricity and effectively isolates generation and utilization of electricity. This will eliminate the peak valley difference of day and night power consumption, improve resource utilization efficiency, and enable large-scale connection of renewable energy sources to the grid. Energy storage application improves the peak shaving and frequency modulation ability of the power system, reduce the investment in development of peak-shaving power plants reserve capacity, and expansion of power transmission and distribution[324]. EES technology has wider applications in power systems

due to their high-energy density, fast response, high specific power, flexible installation, high reliability, long life, etc. The most commonly used EES technologies lead, lithium iron, flow batteries, Na-S, and super capacitors.[324].

17.2. The International Installed Capacity of Energy Storage and EES

By the end of 2020, about 191.1 GW of energy storage capacity had been put into operation globally with the proportion of EES being about 7.5%, exceeding 10 GW with lithium ion batteries having the largest capacity accounting for about 92% of the total installed capacity of EES[324]. The global installed capacity of storage is shown in Figure 17-1.

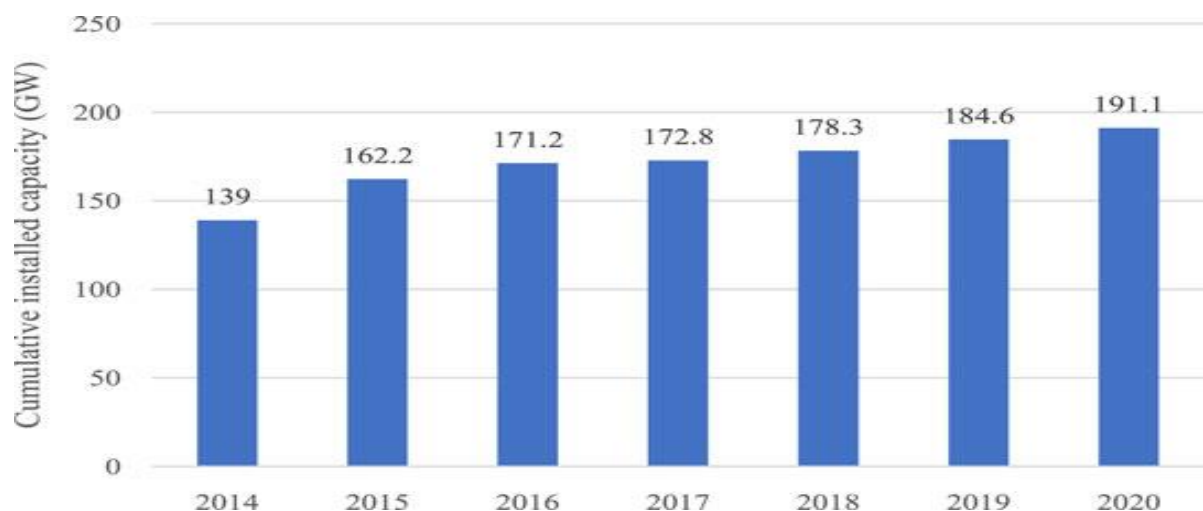


Figure 17-1: Global installed capacity of storage.

Figure 17-1 shows the global installed capacity of storage between 2014 and 2020. It shows that capacity grew from 139 GW in 2014 to 191.1 GW in 2020.

Different storage technologies used globally right from electrical to thermal storage technologies. They are showed in Figure 17-2.

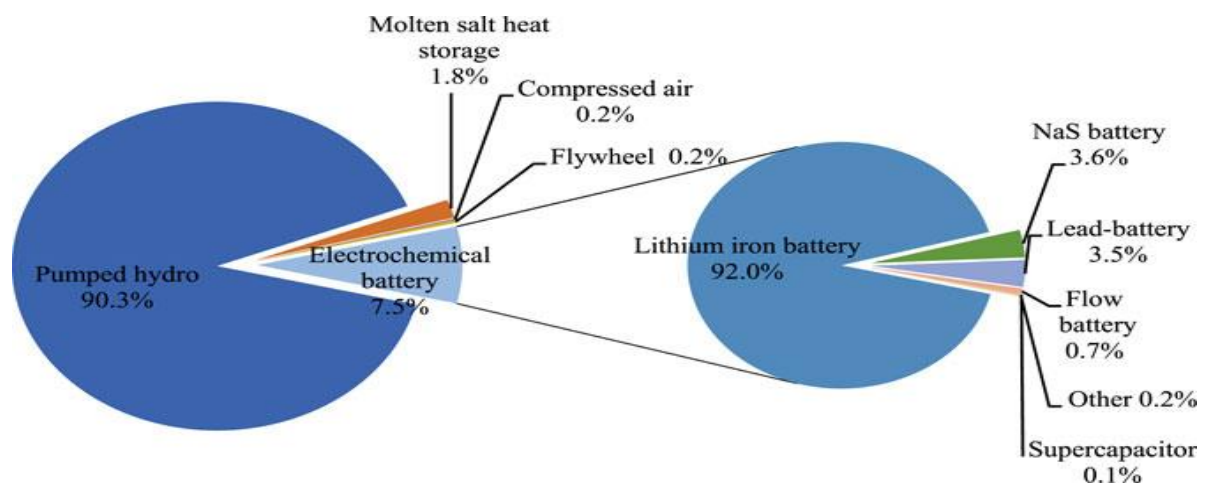


Figure 17-2.: Share of different storage technologies.

From Figure 17-2, it is noted that pumped storage is the most dominant technology used accounting for about 90.3 % of the storage capacity, followed by EES. By the end of 2020, the cumulative installed capacity of EES had reached 14.2 GW. The lithium-ion battery accounts for 92% of EES, followed by NaS battery at 3.6%, lead battery which accounts for about 3.5%, flow battery 0.7%, supercapacitor 0.1% and others 0.2%.

The cumulative installed capacity and growth rate of the global EES in 2014–2020[324] are shown in Figure 17-3.

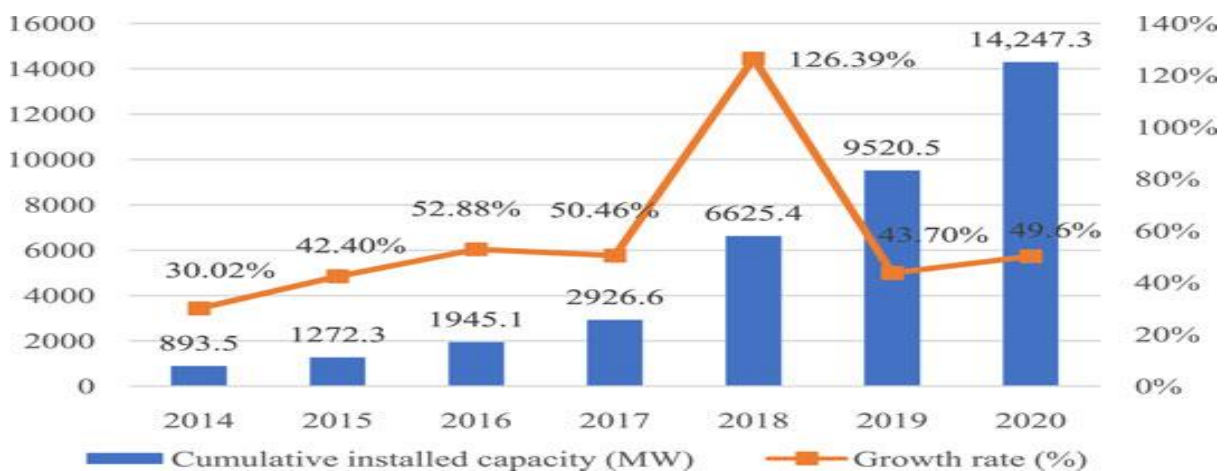


Figure 17-3: Cumulative storage capacity of EES

From Figure 17-3, it is shown that the cumulative storage capacity of EES grew from 893.5 GW in 2014 to 14.247.3 kW in 2020. The highest growth in capacity was realized between the year 2017 and 2018 at 126.39% and the least growth was realized between 2024 and 2015 at 30.02%.

17.3. Types Grid Scale Storage Battery Solutions

According to the Energy Storage Association of North America, market application of batteries is divided into in-front of the meter (FTM) and behind-the-meter (BTM) applications. Front of meter (FTM) batteries are systems connected to distribution or transmission networks or can be connected to the generation asset providing services like ancillary services or network load relief. Behind-the-meter (BTM) batteries are interconnected behind the utility meter of customers, aimed at electricity bill savings through demand-side management[321, 326]. There are many types of commercially available batteries globally e.g. Lithium-ion (Li-ion), absorbed glass mat valve-regulated lead-acid (AGM-VRLA), gel valve-regulated lead-acid (Gel-VRLA), Lead-carbon (LCB), and

Aqueous Ion Hybrid (AIHB) batteries[319]. The most extensively used rechargeable batteries are the Lead batteries mainly due to their reliability, safety and well-established worldwide supplier base [1016].

17.4. Solid State Versus Flow Batteries

The solid-state batteries store energy in solid electrode material like metal, while flow batteries store energy in electrolyte liquids. Many conventional energy storage batteries with flow batteries make use two electrolyte liquids, with one at the anode and the other at the cathode.

17.4.1. Solid State Batteries

A Solid-state battery use a solid electrodes and a solid electrolyte, instead of a liquid or polymer gel electrolytes used in lithium-ion or lithium polymer batteries. [1017]. The solid-state batteries have potential solutions to many challenges facing liquid Li-ion batteries, like flammability, low voltage, unstable solid-electrolyte interphase formation, low strength, and poor cycling performance. Common materials used in solid electrolytes include ceramics like oxides, sulphides, phosphates, and solid polymers. These solid batteries have applications like pacemakers, RFID and wearable devices. Solid batteries are relatively safer, have higher energy densities, but are more expensive and have lower durability, high material costs, sensitivity and stability[1017, 1018]

17.4.2. Flow Batteries

Flow batteries have been explored since the 1970s, for application in electric utility storage in the USA and Japan. Flow batteries store energy in electrolyte solutions and contain two redox couples (e.g., V/V, Zn/Br₂, V/Br₂, S/Br₂, Ce/Zn, Fe/Cr, and Pb/Pb) which flow through a power battery/reactor and involve a reversible chemical reaction. Two electrodes of a flow batteries are separated in different electrolyte tanks. Unlike traditional energy storage battery technologies, the electrode and electrolyte of flow batteries are separated, and the energy capacity of the flow battery is influenced by the size of the electrolyte tanks, while the battery power depends on the size of the battery[32, 553].

Liquid electrolytes used in flow batteries are characterized by high ionic conductivity like $\sim 10^{-3} \text{ S cm}^{-1}$ at room temperature with almost no electronic conductivity, can operate well over a wide range of temperature from tens of degrees below 0°C to about 100°C. The main disadvantages of liquid electrolyte batteries are high flammability, highly resistive at electrodes leading to capacity loss, electrolytic decomposition at high voltages which limit

use of high voltage cathode materials, formation of HF at thermal runaway, and the risk of leakage. [1018]. For grid scale applications, we have three types of flow batteries namely.

i. Zinc–Bromine Flow Batteries

Zinc–bromine flow batteries offer several advantages, high specific energy density (75–85 Wh/kg), high flexibility, and low cost. The commercial development is limited by dendrite formation tendency of zinc, low energy efficiency, poor cycle life, and high solubility of bromine in the aqueous zinc bromide electrolyte[32, 553].

ii. Vanadium Redox Batteries

Vanadium redox batteries use sulfuric acid containing V^{5+}/V^{4+} and V^{3+}/V^{2+} redox couples as positive and negative half-cell electrolytes. The advantages of vanadium redox batteries include high battery efficiency of 75–85%, long lifetime of 12000 to 14000 cycles, high safety standards, cheap to operate, and easy to maintain. The vanadium redox batteries are capable of deep discharge and good for stationary applications[318].

The limitations of these batteries include large space requirement due to relatively low energy density of 10–50 Wh/kg. The vanadium redox battery technology is mature GLEES e.g., 15 MW vanadium redox batteries were fabricated at Minamihayakita Transformer Station in Abira-Chou, Hokkaido, to supply power for 4 hours. Additionally, the China National Energy Administration approved a vanadium redox battery system of 200 MW capacity in Dalian, China, in 2016[1019].

iii. Polysulfide Bromide Batteries

Polysulfide bromide batteries also operate based on the redox reaction using a cation-selective membrane like Nafon. Polysulfide bromide batteries generally have energy density of about 30 Wh/kg and are ideal for voltage and frequency regulation in GLEES because of their fast response time. The batteries through have relatively low efficiency of ~ 60–75% mainly due to pumping requirements. The practical application of polysulfide bromide batteries faces challenges like high cost of carbon felt, the complicated preparation method of sodium polysulfide, and cross-contamination during long-term battery operation. The Regenesys technologies successfully commissioned the normal operation of a polysulfide bromide battery plant with 120 MWh, 15 MW power capacity at Innogy's Little Barford Power Station in the UK and in Columbus, Mississippi, in the USA[318]. This shows the significant potential of polysulfide bromide batteries in grid scale applications.

17.5. AGM-VRLA Batteries (Lead –Acid (LA) Cells)

The Lead-acid (LA) cells are widely used in BESS technologies in applications like solar traffic lights, telecommunications, automotive, uninterruptible power supplies (UPS), energy storage devices and many others. There are three distinct designs of lead acid batteries having different structural and functional characteristics. The flooded or vented design has a large amount of liquid electrolyte (sulfuric acid) in which the electrodes are immersed and needs periodic watering to limit electrolyte depletion. The other two are sealed and valve-regulated (VLRA) lead-acid batteries, that contain minimal amount of electrolyte, and need no watering [319].

The main advantage of the VRLA batteries is their quick charge capabilities, high power density, and low maintenance requirements. Their basic components are the positive and negative plates, an electrolyte, and a separator used to immobilize the electrolyte. Separators are absorptive glass mat (AGM) or silica particles, which react with sulfuric acid to form a gel. The separators are made of glass microfibers obtained based on a paper-making process and wicked the sulfuric acid between the plates. This separator makes the AGM battery spill-proof and can make their shipping easy. The AGM batteries have a high discharge rate with low internal resistance and provide electrical reliability due to their low maintenance requirements. These batteries have between 500 and 2500 life cycles at a depth of discharge (DoD) of 30–50 % and efficiency of 80–90 %, and are widely used for household and industrial consumers[319].

17.6. Gel-VRLA Batteries (GEL-Batteries).

A gel battery has gelled electrolyte whose quality has a significant impact on its battery characteristics. Fumed and colloidal silica are the most widely used gelling agents with the first one being more reliable under deep-discharge conditions, but with shortcomings like an increased internal resistance and high production costs. The colloidal silica gels are simple to prepare and use lower material cost, but has higher impurities content of impurities like iron leading to high water consumption, and increased production costs[319].

The Gel-VRLA is superior to the AGM technology, in terms of higher reliability due to their high deep-discharge performance, long service life of over 12-year, small self-discharge rate, good charge stability. The Gel-VRLA can reach 4500 cycles at 40 % DoD with and efficiency of 90 % to 99 %[319].

17.7. Lead-Carbon Batteries (LCBs)

The Lead-carbon batteries (LCBs) are suitable replacement for conventional lead-acid technologies because of their longer cycle life under deep charge/discharge partial-state-of-charge operation conditions. Carbon and electrolyte additives can be used to lower the hydrogen reaction rate in the batteries which can increase the lifecycle, and enhanced the reversibility of deep cell discharge. These batteries have between 500 and 2500 life cycles at 50–100 % DoD, at charge/discharge efficiency of 90–99 % [319].

17.8. Lithium-ion Batteries (Li-ion)

The first commercial Li-ion batteries were made in 1990 by Sony, but they are one of the most important type of batteries, leading the market in the field of energy storage. The Li-ion battery is operated by Li^+ moving back and forth between two electrodes by inserting or extracting from the interstitial space existing between atomic layers of electrode materials during discharge–charge processes. The battery construction comprises of positive and negative electrodes and a Li-ion-conducting electrolyte [319].

The positive electrodes materials in the Li-ion batteries are metal oxides having layered or tunneled structures like., lithium cobalt oxide [LiCoO_2], lithium manganese oxide [LiMn_2O_4], LiFePO_4) on an aluminum current collector. The battery's negative electrode usually consists of graphitic carbon on a copper current collector. The electrolytes can be liquid electrolytes or semisolid/solid-state electrolytes. The Liquid electrolytes are generally lithium salts (e.g., LiPF_6 , LiBF_4 , $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ and lithium bis-oxalato borate [LiBOB]) dissolved in organic carbonates like propylene carbonate, ethylene carbonate, dimethyl carbonate, ethyl methyl carbonate, and diethyl carbonate and their mixtures. For semisolid electrolyte, a polymer electrolyte which is ion-conducting material composed of lithium salts and high-molecular-weight polymer matrices like poly (ethylene oxide), polyvinylidene fluoride, polyvinylidene fluoride-hexafluoropropylene) with or without solvents are used [318, 322].

The Li-ion batteries are characterized by a long cycle life higher than 1000 cycles, low self-discharge of 2-8% per month, high efficiency of almost 100%, and wide operating temperature range e.g., commercial Li-ion batteries may charge between 0 and 45 °C and discharge between –40 and 65 °C. The batteries (Li-ion batteries) can be produced into a wide array of sizes and shapes, like flat or “stacked” prismatic, wound prismatic, spiral-wound cylindrical, and pouch cell designs in small (0.1 Ah) to large (160 Ah) sizes [1, 32].

However, major disadvantages of Li-ion batteries include their relatively low energy density (240 Wh/kg, 640 Wh/L), potential degradation potential when discharged below 2 V at high temperature e.g. 65 °C and are dangerous when overcharged.[318].

17.9. Sodium–Sulfur (Na–S) Batteries

Sodium Sulfur (NaS) batteries were developed originally by the Ford Motor Company in the 1967, but the technology was sold to the Japanese company NGK which manufactures battery systems for stationary applications. Na-S operate at a high between 300 to 350 °C temperature range which can be a challenge in intermittent operations. The battery systems have round trip efficiency of about 90% making it an efficient energy solution[1016]. The sodium -sulfur (Na–S) batteries consist of molten Na anodes, molten S cathodes, and Na⁺-conducting ceramic electrolytes (e.g., β "- Al₂O₃) and operate between 300–350 °C. The S cathodes are generally filled in a conductive porous carbon or graphite felt as current collectors. The casing for Sodium -sulfur batteries is made of stainless steel. The Na–S battery has a theoretical energy density of 760 Wh/kg, while real or practical energy and power density is 150–240 Wh/kg and 150–230 Wh/kg[32, 553],

Compared to Li-ion batteries, the Na–S batteries have relatively long cycle life of about ~ 2500 cycles and efficiency of 75–90%. Additionally, the Na–S batteries can handle pulse power for more than six times their continuous rating (for 30 s). This makes them ideal for energy storage devices for GLEES for applications like peak shaving and load leveling. The Na-s batteries operate with high specific energy and power density, high current and rate capacity, high self-discharge resistance, high electrical efficiency, low vibration, low noise, and high environment friendliness. The main draw backs of the of Sodium sulfur batteries is that they need a heat source and the reaction is highly exothermic between molten Na and S which increases fire risk, The initial capital cost of Na–S batteries is about ~\$350/kWh, although it is expected to drop with increased production[318].

17.10. Aqueous ion Hybrid Batteries (AIHBs)

The AIHBs are attractive due to high safety performances and ionic conductivity among all rechargeable batteries and are suitable for medium and large-scale applications. The AIHB technology employs similar electrodes to those used in Li-ion batteries. The electrolyte is based on an aqueous solution which reduces their environmental impact compared to the Li-ion batteries. The aqueous ion hybrid batteries (AIHBs) are however still under research and development stage though some commercially available solutions are available. The life of

the AIHBs BESS is about nine years which is approximately 3,000 life cycles at a 70 % DoD and a charge/discharge efficiency of about 90 %[319].

Aqueous hybrid ion batteries (AHIB) are regarded as environmentally friendly alternative to existing stationary battery technologies. The AHIB uses abundant and non-toxic materials, but has low energy density and requires more material to provide sufficient energy storage capacity. Analysis however shows that compared to lithium- or sodium-ion batteries they have significantly higher impacts under global warming and ozone depletion aspects. The AHIB have high cycle life which compensates for the impacts partially because they require less battery replacements over the lifetime of the application. The AHIB has relatively high internal inefficiencies which becomes significant if charging is by fossil fuel based electricity, making AHIB batteries unattractive [1020].

17.11. Electrochemical Capacitors

Electrochemical capacitors (ECs) are also called the “electric double-layer” capacitors – or “Supercapacitor” or “Ultracapacitor.” The phrase “double-layer” implies that they physically store electrical charge at a surface-electrolyte interface of high-surface-area carbon electrodes. Two main types of electrochemical capacitors are symmetric and asymmetric and have different properties that are suitable for different energy storage applications. The market for electrochemical capacitors is on growth trajectory for applications in grid scale electricity storage among others[1019, 1021].

An electric current flow when two electrodes of an electrochemical capacitor are connected in an external current path, until complete charge balance is achieved. Application of voltage returns the capacitor to its charged state[32, 553]. The process is fast and highly reversible with a limitless discharge-charge cycle since the charge is stored physically, with no chemical or phase changes taking place. The electrochemical capacitors have very high specific and volumetric capacitances due to their high surface area and the small thickness of the double layer which enables a combination of a previously unattainable capacitance density with almost unlimited charge-discharge cycle life. One cell of an electrochemical capacitor has operational voltage of one cell is limited by the breakdown potential of the electrolyte usually about 3 V or less. Higher voltage is obtained by connecting many cells in series[1022, 1023]. Figure 17-4 demonstrates the construction of the electrochemical capacitor.

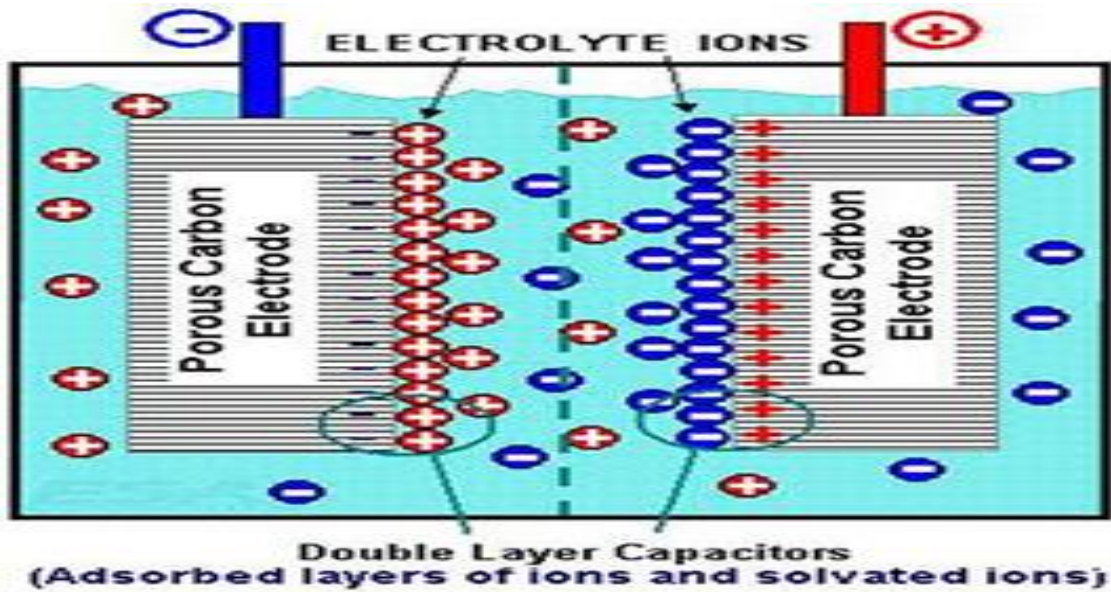


Figure 17-4: Electrochemical Capacitors

Figure 17-4 shows the basic construction of an Electrochemical Capacitor which has a porous carbon electrode at the cathode and a porous carbon electrode for the anode.

There are two types namely, the symmetric designs, where both positive and negative electrodes are made of the same high-surface-area carbon and the asymmetric designs which have different materials used for the anode and cathode electrodes, with one having high-surface-area carbon and the other a higher capacity battery-like electrode. The Symmetric electrochemical capacitors have specific energy values up to ~ 6 Wh/kg and higher power performance compared with the asymmetric capacitors which have specific energy values of about 20 Wh/kg[1022].

The market for electrochemical capacitors has been growing mainly because of their high-power density, long cycle life, high reliability, etc. Their main applications are in portable electronics, transportation, and medical devices and are preferred for applications which require high cycle life and fast charge or discharge times of 1 second or less. The main limitation of electrochemical capacitors is lack of understanding of the technology and limited ideal applications[1023].

The Symmetric electrochemical capacitors have a response time of the order of 1 second and hence suitable for short duration high-power applications related to both grid regulation and frequency regulation. Asymmetric electrochemical capacitors are more suitable for energy storage applications. Some asymmetric electrochemical capacitors are optimized for ~ 5 -hour charge with ~ 5 -hour discharge. The main advantages of electrochemical capacitors are long

cycle life, good efficiency, low life-cycle costs, and adequate energy density[1021, 1022]. The Electrochemical capacitors (ECs) are used to bridge the gap existing between batteries and solid-state and electrolytic capacitors. The high-power density makes them more attractive, since greater energy density is needed for the future. [1024].

17.12. Nickel–Metal Hydride (Ni–MH) Batteries

Ni–MH batteries were first studied in the 1960s and have been in the market for over 20 years as portable and traction batteries Ni–MH batteries are made of metal hydride anodes like AB₅-type [LaCePrNdNiCoMnAl], A₂B₇-type [LaCePrNdMgNiCoMnAlZr], or AB₂-type [VTiZrNiCrCoMnAlSn] metal hydride active materials), nickel hydroxide cathodes, and alkaline electrolytes (e.g., KOH, KOH/ LiOH, KOH/NaOH/LiOH). The batteries make use of a separator as an insulator between anodes and cathodes, and functions as the medium for absorbing electrolytes. It is composed of synthetic nonwoven material. The Ni–MH batteries have porous anode and cathode with a large surface area, which provide low internal resistance. and high-rate performance capability. The cathode is made by impregnating or pasting nickel compounds into the foam nickel or a highly porous sintered substrate, and the while the anode is a hydrogen-storage-alloy-coated perforated nickel foil or grid. The Ni–MH batteries are generally used in telecommunications, for supply of uninterrupted power and to power hybrid electric vehicles because of their high energy and power (40–110 Wh/kg, 200–1200 W/kg) [32, 553],

The main advantages of the Ni-MH batteries are environment friendly, have a wide range of operating temperatures (–30 to 70 °C), high degree of tolerance to abusive overcharge and over discharge, long-life characteristics, low maintenance, and low cost. The major [318]

17.13. BESS Input Data

Battery energy storage systems have different performance parameters and indicators, based on type of battery technology, the manufacturer, the operating environment, and conditions i.e. temperature, maximum current, voltage, and power and maintenance needs. The analysis assumes that for 24-hours period, the battery is fully charged and discharged at the various design like recommend DoD specified in the technical/commercial datasheets by the distributor, calendar life (n) and number of cycles considered per year i.e. (365 days). The input parameters for various BESS systems are presented in Table 17-1.

Table 17-1: Input parameters for the analyzed BESS technologies[319].

		AGM-VRLA	Gel-VRLA	LCB	Li-ion	AIHB
1	Nominal voltage	6–12	2–12	6-12	12–600	48
2	Rated capacity [Ah]	22–460	17–3170	70–300	8.33–500	50
3	Rated energy [kWh]	0.264–3.48	0.204–14.4	0.84–3.264	0.3–25.6	2.4
3	Battery efficiency [%]	80–90 %	80–95 %	90–99 %	90–99 %	90%
4	DoD [%]	30–50 %	30–60 %	50–100 %	50–100 %	70
5	Cycles at DoD	400–2500	550–4500	500–2500	2000–7000	3000
6	Calendar life (<i>n</i>) years	2-7	2-13	2-7	6-20	9

From Table 17-1, it is noted that in terms of normal voltage, the Li-ion batteries are superior, LI-ion and LCB are superior in terms of efficiency. Batteries that exhibit lower or inferior DoD (depth of discharge) on an average basis are the AGM-VRLA and Gel-VRLA. The AIHB and Li-ion have a higher average useful life.

17.14. Sustainability of Storage Systems

17.14.1. Levelized Cost of Energy Storage Technologies

There is no generally accepted economic indicator for comparison of different energy storage systems, unlike in the planning of power plants which mainly use the “Levelized Cost of Electricity (LCOE)” which has now been modified for application in electrical energy storage systems, this derived indicator is called “Levelized Cost of Storage (LCOS)”. Levelized cost of storage is the total lifetime cost of the investment in an electricity storage technology divided by its total or cumulative delivered electricity delivered. This reflects the internal average price that the electricity is sold for the project’s net present value to be zero. The Levelized cost of storage (LCOS) for various technologies and life cycle cost of energy (LCOE) for generation technologies can be compared directly but involve different concepts of providing electricity and leading to differences in cost calculation methods hence their

different names [369]. However, the LCOS calculation procedure is not yet approved but its popularity has been growing [605]. Levelized cost (LCOS) quantifies discounted cost per unit of power discharged for a given storage technology and application. Therefore, the Levelized cost of energy is used to account for the technical and economic parameters that affect the lifetime cost of discharging stored electricity. Levelized cost of storage is equivalent to Levelized cost of electricity (LCOE) for generation technologies, but represents an appropriate tool used for comparing the costs of storage technologies[369].

Levelized cost of storage (LCOS) is applied in various investigations to assess different storage technologies e.g. pumped-storage hydroelectricity, compressed air energy storage, battery technologies like Lithium-ion, Lead and Vanadium redox flow batteries and power to gas[319, 320]. About 7200 gigawatts (GW) of electricity capacity must be built globally to keep pace with growing electricity demand and to replace retiring power plants by 2014. Future power systems are expected to have large proportions of intermittent power like wind, solar and tidal generation and or inflexible. nuclear, coal, *etc.* There is need to scale up storage scale-up energy storage to match the electricity supply with hourly, daily, and seasonal electricity demand profiles. According to the International Energy Agency, about 310 GW grid grid-connected electricity storage capacity will be needed by the US, Europe, China and India[325].

The LCOS analysis determines the total cost for one kWh stored by each type of the analyzed BESS. It includes the capital expenditure (CAPEX), operation, maintenance (OM) and charging (C) costs over the entire lifetime (n) of the storage system divided by total energy generated by the storage system (W_{out}) in the entire lifetime. The annual costs and energy output are then discounted considering a discount rate i e.g. 8.5%.[319].

The other cost parameters for consideration are annual operation and maintenance costs. which vary with storage technology. Values may be computed as percentages of CAPEX i.e. 0.5 % for lead-acid/carbon technologies and 0.25 % for Li-ion and AIHB batteries [319]. Charging costs per year (C) is price of electricity used for battery charging hence not injected into the grid. This represents the money that a prosumer receives if he decided to store the surplus for later instead of supplying it to the grid.[319]. The CAPEX, OM and C costs of battery storage is established based on market analysis. The analysis gives a wide range of values for each cost factor analyzed in the study. This implies that the same battery or system may have may have different costs, based on the manufacturer and distributor[319].

Identification of a representative value for each technology requires the use of an interquartile range (IQR). to remove outliers for each cost factor. The IQR determines values between the first and third quartiles, spread out around the data' median and indicates the middle (50 %) of the series. Based on the median, the first and third quartiles are determined. The difference between the quartiles defines the IQR. The average (Avg) of IQR is computed to represent each cost factor's representative value[32, 553]. The range values, IQR and Avg for the primary cost parameters used to determine LCOS values are presented in Table 17-2.

Table 17-2: Main cost parameters of BESS technologies[319].

			AGM- VRLA	Gel- VRLA	LCB	Li-ion	AIHB
1	C _{BESS} [€/kWh]	Range	77.55– 248.78	55.95– 516.55	143.34– 219.81	233.35– 2397.68	470.40
		IQR	119.04– 172.58	110.87– 191.01	156.22– 192.55	373.56– 769.37	
		Average	146.59	142.03	180.01	568.89	
	VAT [€/kWh]	Range	14.73– 47.27	10.63– 98.14	27.23– 41.76	44.34– 455.56	89.38
		IQR	22.62– 32.79	21.06– 36.29	29.68– 36.58	70.98– 146.18	
		Average	27.85	26.99	34.20	108.09	
	DS [€/kWh]	Range	9.23– 29.61	6.66– 61.47	17.06– 26.16	27.77– 285.32	55.98
		IQR	14.17– 20.54	13.19– 22.73	18.59– 22.91	44.45– 91.55	
		Average	17.44	16.90	21.42	67.70	

S _{BESS} [€/kWh]	Range	30.45–	21.97–	56.29–	91.64–	184.73
		97.70	202.85	86.32	941.57	
	IQR	46.75–	43.54–	61.35–	146.70–	
		67.77	75.01	75.61	302.13	
	Average	57.56	55.77	70.69	223.40	
OM [€/year]	Range	0.28–	0.42–	0.84–	1.33–	3.69
		4.57	14.30	3.51	33.32	
	IQR	1.08–	1.09–	1.48–	3.17–	
		2.10	2.20	2.63	12.98	
	Average	1.55	1.59			

From Table 17-2, it is noted that the 4 batteries compared, i.e. Aqueous ion Hybrid Batteries (AIHBs), Lead-Carbon Batteries (LCBs), Lithium-ion (Li-ion), absorbed glass mat valve-regulated lead-acid (AGM-VRLA), gel valve-regulated lead-acid (Gel-VRLA), Lead-carbon (LCB), and Aqueous Ion Hybrid (AIHB) batteries have different cost and performance characteristic. The Li-ion batteries exhibit superior technical properties.

Two values of LCOS were determined for the batteries. First, LCOS does not include subsidies while the second includes subsidies. The second LCOS i.e. (LCOS₂) includes subsidies provided. The average values obtained are summarised in Table 17-3.

Table 17-3: LCOS for the examined BESSs technologies[319].

		AGM-VRLA	Gel-VRLA	LCB	Li-ion	AIHB
LCOS ₁ [c€/kWh]	Range	27.75–	20.41–	28.87–	18.68–	50.76
		109.29	132.3	54.33	157.62	

	IQR	41.79–80.39	36.28– 65.98	31.6–42.95	25.96–76.57	
	AVR	54.58	48.13	39.04	45.6	50.76
LCOS ₂ [c€/kWh]	Range	22.23–79.76	17.01–95.6	22.78– 39.49	14.5–112.9	37.64
	IQR	32.42–59.12	28.45– 49.01	24.57– 32.53	19.7–55.54	
	AVR	41.18	36.91	29.39	33.63	37.76

Table 17-3 shows the LCOS₁ and LCOS₂. Based on average values, the lowest values for LCOS₁ and LCOS₂ are for the LCB battery technology at 39.04 to 29.39c€/kWh. They have high DoD of 50–100 %, conversion efficiency higher than 90 % and low battery cost of 180.01 €/kWh), hence more electricity at low battery cost. The Li-ion battery with 45.6 and 33.63c€/kWh offer the second best LCOS other some studies have shown higher values of between 61.1c€/kWh and 83c€/kWh. Clearly the battery prices are on a decreasing trend mainly due to incentives and taxes[319]..

17.15. Thermal Storage

The various forms of thermal storage include chilled water tank, and ice storage whose operation fit in the operation of the energy source and supply profile e.g. a chiller linked to solar only starts operation if the PV power is available at a specific supply level and cuts off when, PV power supply drops below the threshold or its demand capacity[1025]. Cold thermal energy storage can be used in or demand side management, for reduction of peak-loads. [1026]. Thermal energy storages, applying chilled water or ice as storage medium, can be used in cooling systems to benefit from lower night tariffs or to avoid chiller electricity consumption peaks (peak electricity rates) in district cooling systems while larger office buildings storage systems can be applied to maximise photovoltaic (PV) energy self-consumption[296, 1025].

A Pumped Heat Energy Storage system can be used to store thermal energy by applying a proprietary reversible heat pump (engine) which compresses and expands the gas. The system

uses two thermal storage tanks for storage of heat at the temperature of the hot and cold gas. Analyzing the LCOS with other storage technologies of size 100 MW and 400 MWh showed that Pumped Heat Energy Storage is cost-competitive with Compressed Air Energy Storage systems as well as pumped hydroelectricity storage with the additional advantage of full flexibility for location[325, 386].

17.16. Results and Discussion

The cumulative installed capacity of lithium-ion batteries is highest of the chemical storage batteries accounting for about 88.8% of electrical energy storage (EES) in China for the year 2020. Lead-carbon batteries have highest safety due lack of combustibles during operation and are increasingly used for large-scale EES technology. The initial cost of vanadium redox flow is high, the cost will reduce as development of technology and industry progresses[32, 553]. The batteries have a very flexible scale design. The electrolyte capacity and concentration influence energy storage capacity, thus increasing volume of the electrolyte increases energy storage capacity. This makes the vanadium redox flow the most promising large-scale electrical energy storage (EES) technology in the future.[324]. The LCOS for the thermal energy storages are usually lower than that of the battery, at 23–47 USD ct/kWh[1025].Energy storage is essential for implement the large-scale integration of renewable energy for the current and future transition to a 100% renewable energy supply. An electricity-only focus – as in a smart grid approach – leads to options primarily focused on electricity storage technologies in combination with flexible electricity demands and transmission lines to neighbouring countries[388].

Grid-level large-scale electrical energy storage (GLEES), which entails converting electricity from a grid-scale power network to a storable form for later conversion to electricity, has an important role in delivery of plays an essential role to play in the balance of demand and supply of electricity. Many storage technologies ae available like secondary battery technologies and supercapacitors, flow batteries, compressed air, flywheels, thermal energy storage, and pumped hydroelectric power. Battery technologies are considered as one of the most desirable electrochemical energy storage devices for grid-level large-scale electrical energy storage (GLEES) in terms of modularization, flexibility of installation, rapid response, and short construction cycles. The energy storage technologies serve the following functions:

- i.) peak shaving and load leveling.
- ii.) voltage and frequency regulation; and

iii.) emergency energy storage[318].

Peak shaving and load leveling is used to mitigate the peak-to-valley power demand gap between the night and the day when a renewable resource is available and when it is not available or is limited. Voltage and frequency regulation are applied in a nonuniform electrical load of the grid network for realization of a real-time power system balance by providing power regulation to the grid by charging and discharging with a fast response time[318].

In studies involving analysis of energy to power ratio, construction and commissioning costs, balance of plant, and capital cost required, pumped storage hydro, compressed air and Li-ion ranked favourable against other storage technologies [28. A more detailed study report is presented in Table 17-4.

Table 17-4: levelized Cost of Storage[1027]

Storage Technology	Capital Cost (\$/kWh)	BOP (\$/kWh)	PCS (\$/kWh)	C&C (\$/kWh)	O&M (\$/kWh)	Total (\$/kWh)	RAN K
Sodium-sulphur	\$87.25	\$3.30	\$11.55	\$17.56	\$2.92	\$122.58	6
Li-ion	\$43.49	\$4.01	\$11.55	\$11.55	\$2.91	\$73.51	3
Lead acid	\$101.31	\$9.74	\$34.09	\$68.58	\$2.70	\$216.42	9
Sodium metal halide	\$96.18	\$3.43	\$12.02	\$15.80	\$2.89	\$130.32	7
Zinc-hybrid cathode	\$42.53	\$4.01	\$14.04	\$27.76	\$2.91	\$91.25	4
Redox flow	\$73.19	\$3.30	\$11.54	\$25.06	\$3.04	\$116.13	5
Pumped storage hydro	\$18.03	\$0.00	\$0.00	\$0.00	\$1.24	\$19.26	2
Compressed	\$11.39	\$0.00	\$0.00	\$0.00	\$1.30	\$12.69	1

air							
Flywheel	\$2,936.0	\$0.00	\$0.00	\$56.76	\$76.39	\$3,069.19	10
	4						
Ultracapacito	\$6,893.6	\$1,719.1	\$6,016.9	\$10.22	\$240.43	\$14,880.3	11
r	7	2	2			6	
Combustion	\$111.39	\$0.00	\$0.00	\$0.00	\$38.07	\$149.46	8
turbine							

Table 17-4 shows the levelized cost of storage of various available options. The total Levelized cost is divided into PCS, (power conversion system), BOP (balance of plant), C&C (construction and commissioning), O&M (operations and maintenance).

From table 16.4, it is noted that compressed air storage followed by pumped hydro and Li-ion respectively offer the cheapest energy storage solutions based on their Levelized costs of energy. On the other hand, the ultra-capacitor, the flywheel, and the Lead acid batteries are ranked as the three most expensive energy storage solutions based on their computed levelized cost of energy.

A possible pathway to increase the business case for electricity storage is through multiple services using the same device which brings multiple revenue streams also called “benefit-stacking”. The nominal power capacity is based on the largest service i.e., sequential stacking or the sum of all service provided at the same time i.e., parallel stacking. The discharge duration reflects the sum of durations required by all services for sufficient energy capacity when all services are needed in parallel or directly one after another. The full equivalent cycles also reflect the respective sum for all services provided by the system. Average electricity price could be the sum of prices captured during charging for individual services weighed by the full equivalent cycles attributed to them[369].

Levelized cost of storage varies with different application scenarios e.g., for transmission and distribution applications. LCOS is the lowest when lithium iron phosphate batteries are used because the batteries only need one replacement taking advantage of long life. Therefore, improving round-trip efficiency and storage duration, reducing the unit initial investment cost, and giving full play to the advantages of different technology types when laying out EES can be used to reduce costs. The use of LCOS is dependent on economic storage

characteristics and, unlike the traditional Levelized cost of energy (LCOE) which also depends on the temporal characteristics of the electricity price profile. Hence an analysis the whole power system will provide more information than a single Levelized cost measure to compare different storage technologies in the electricity market.

The lead batteries have wide applications in telecommunications, uninterrupted power supply, electric traction, and energy storage for utilities, secure power, electric traction, and other domestic and commercial applications. The Levelized Cost of Storage is a metric often applied to assess the economic competitiveness of different energy technologies. The lowest Levelized Cost of Storage occurs when the system is designed for continuous operation, instead of peak shaving. Solar Photovoltaics can guarantee output within economically feasible limits, although they are slightly currently expensive.

17.17. Conclusions

Energy storage systems like the grid-level large-scale electrical energy storage (GLEES) plays an essential role in the balancing of the supply-demand of electricity generation, distribution, and consumption and is therefore a critical component of the global energy transition. The various storage approaches available include secondary battery technologies and supercapacitors, solid and flow batteries, flywheels, compressed air energy storage, thermal energy storage, and pumped hydroelectric power. Storage is required for peak shaving and load leveling, voltage and frequency regulation and emergency energy storage. The peak shaving and load leveling are applied to mitigate the peak-to-valley power demand gap between day and night, while voltage and frequency regulation are useful in nonuniform electrical load of the grid network to enable real-time power supply and demand balance with storage providing regulation power to the grid by charging and discharging with a fast response time.

Storage may not be the optimum solution to integrate large fluctuating renewable energy, due to availability of more efficient and cheaper options for integration of electricity with other parts of the energy system and development of a smart energy Systems. However, storage remains important for large scale integration of variable renewable to the electric power systems. An optimal storage solution must go beyond the lowest levelized cost of storage and consider other parameters like Depth of Discharge (DoD), number of cycles which define the technical capacity of storage technologies. The electro-chemical capacitors are used to store electrical energy from intermittent sources and for quick delivery when needed. The

Electrochemical capacitors (ECs) are used to bridge the gap existing between batteries and solid-state and electrolytic capacitors. The high-power density makes them more attractive since greater energy density is needed for the future.

17.18. Recommendations

Energy storage is an important component of the grid and should be incorporated in electricity grids for balancing which increases uptake of variable sources of energy and loads. Using storage along with smart grids and microgrids will enable optimal integration of storage on the grid effectively treating storage as secondary grid scale power plants will help in the realization of the net zero emissions target set by the world community.

CHAPTER 18:

THE ROLE OF TRANSPORT SECTOR AND V2X TECHNOLOGIES IN THE ENERGY TRANSITION

18. Overview

This chapter contains work published in paper [35] as a conference paper on electrification of the transport sector and its role in the energy transition. Electric vehicles (EVs) have undergone tremendous advancement because of battery technology advancement and reduction in the cost of batteries. Few years ago, electric vehicles were much expensive compared to the conventional vehicles. The current development is redesign of the infrastructure and further advances in battery technology in terms of charging and charge storage and cost reduction. Road transport is a large emitter of greenhouse gas (GHG) emissions and therefore electric mobility provides huge potential to reduce global greenhouse gas emissions [35]. To realise large scale penetration of electric vehicles (EV), there is need for adequate charging infrastructure. The V2X technologies like V2G, G2V, V2H, V2V provide an opportunity to couple the transport and electricity sectors and enable the electric cars to play a grid role not just as power consumers, but as decentralised power sources as well. The vehicle to grid (V2G) and grid to vehicle (G2V) technology may clustered via aggregator to offer grid power services like load leveling, voltage regulation, and peak shaving, at a lower cost and with less environmental impact. This however requires smart grid technology to enhance the operation and control of electric vehicles making them important energy transition facility. Introduction of electric and hybrid passenger cars, and use of ethanol as a fuel, will help cities the effort to mitigate the greenhouse gas (GHG) emissions by reducing the consumption of fossil fuels. Studies show that emissions from electric vehicles (EV) are significantly less than ethanol if the wheel to wheel (WTW) approach for CO₂ emissions estimation [35].

18.1. Introduction

The transport sector is considered as the most difficult and expensive to reduce emissions and energy demand based on outcomes of forecasting and modelling frameworks that analyse the technical solutions and economically optimal and rational behaviour of individual consumers and markets [35]. The diffusion of advanced vehicle technologies is considered as the core means to decarbonise the transport sector with many promising technologies being at

development level and not yet commercially mature. These technologies include electrification of the passenger vehicle fleets and the V2X technologies [1028].

Projections show that with increase of electric and hybrid vehicles, the transport sector will consume close to 10% of electricity. Charging of many electric vehicles needs meticulous monitoring to avoid a surge of peak loading on the electricity infrastructure. Smart grid technology can facilitate prioritization of charging in cases of low demand exploiting the use of both low-cost generation and extra system capacity. Smart grids synchronize across the value chain from end users to investors and shareholder by significantly reducing the associated costs that come with environmental impacts and enable high system performances[1029].

18.2. Transport Sector Energy Related Emissions and Mitigation

Energy consumption and related carbon emissions pose a serious challenge to the transport sector with about 40% increase in global energy consumption by the sector between 2008 and 2017 with road transport accounting for more than 90% of these consumption [1030].

Energy supply and transport are the most greenhouse gas emitting sectors although the emissions in the energy supply sector have been reducing as more electricity and heat production comes from renewable sources. The use of smart electric vehicle charging can balance variable power generation from renewable sources, potentially allowing higher penetration of renewables. Results from models show that integration of renewables, energy storage and electric vehicles in grid management improves the reliability of the grid and reduces energy costs[61].

New alternative fuels are often associated with sustainable development, efficiency, energy savings, and environmental conservation. A life cycle assessment is recommended whenever new vehicle technologies are developed, for vehicle and the complete fuel cycle from production to fuel use. LCAs are often considered the proper way to compare energy and environmental performance fuels or energy supply[341, 793].

18.2.1. Energy Options for Transport Sector

The various energy and technology options for the transport sector are biofuels, natural gas and biomethane, hydrogen, hybrid technology and electrical traction.

18.2.1.1. Biofuels

These energy options include ethanol, methanol, and biodiesel produced by fermentation biomass like sugar cane, corn, cereals called first-generation biofuels or biomass like wood

and grasses called second-generation biofuels[45, 64, 551]. The main challenge of biofuels is that they compete with food applications like sugar production, etc. The use of ethanol as a transportation fuel is one of the leading measures and policy options to limit emissions in the transport sector[1031].. Ethanol as an engine fuel has less greenhouse gas emissions, when compared with fossil fuels like petrol and diesel[57, 81, 326]. However, ethanol production must increase and its application in transport will have to compete with several other industrial and domestic applications of ethanol to meet the expected increase in demand for energy applications[12, 1032].

18.2.1.2. Natural Gas and Biomethane

Natural gas has been used as a transportation fuel since the early 20th century, but only marginally in the late 20th century. Natural gas is preferred for large fleets of vehicles with extensive travel like public transit buses or delivery trucks. Natural gas accounted for about 4% of transport fuel in 2015 with the share expected to double by the year 2025[57, 164, 387]. Biomethane is a sustainable energy substitute for natural gas use in the transport sector, but governments should put in place measures that will make biomethane competitive in terms of technology and infrastructure [35].

18.2.1.3. Hydrogen

Hydrogen can be used as a fuel for fuel cells used in the transport sector as prime movers. Hydrogen fuel cells are more energy-efficient compared to gasoline and generate near-zero pollutants[34]. The problem is that hydrogen production is energy intensive process and requires electricity. Hydrogen requires low temperature/high-pressure storage tanks which increases weight and volume to the vehicle. Hydrogen may be ideal for ship and aircraft propulsion too[62]. Development of a hydrogen combustion engines to use hydrogen in the place of fossil fuels is an area to explore as another pathway for use of hydrogen fuel in transportation. [35]

18.2.1.4. Electricity

A pure electric vehicle is a more efficient alternative to an engine propelled vehicle. All electric cars are generally easier and cheaper to manufacture similar sized fuel-cell vehicles. The main limitation for electric cars is lack of storage systems that can provide driving mileage like those of conventional vehicles making the electric car less competitive than internal combustion powered vehicles. The range for commercially available electric vehicles is 550 kilometers as in 2022, although the range is increasing. The current technology status

makes electric cars unattractive for long-distance travel with recharging taking between 8 hours for a full charge and 30 minutes for a fast 80% charge compared to standard vehicles which take 5 to 10 minutes to fill the gasoline tank[12, 61].

18.2.2.Hybrid Vehicles

Hybrid vehicles consist of a propulsion system that utilizes an internal combustion engine supplemented by an electric motor and batteries to combine the efficiency of electricity with the benefit of long driving range of an internal combustion engine [35]. The primary source of energy and power is conventional fuels and the engine which also charges the battery via a generator for alternative propulsion. The engine automatically starts when the battery is discharged without a driver's intervention. Braking energy can also be used to power the generator to recharge the battery[1029].

18.2.3.V2X Technologies

V2X technologies refers to vehicle-to-everything and includes arrangements like vehicle-to-home (V2H), vehicle-to-building (V2B) and vehicle-to-grid (V2G) services associated with grid connected vehicles. This is based on the application of electricity from vehicle batteries which can be used to supply power to homes, buildings or the electricity grid[61, 335].

18.2.3.1. Vehicle to Grid (V2G) and Grid to Vehicle (G2V)

Vehicle-to-grid, or V2G, technology is a smart charging technology that enables cars to supply power to the grid by treating high-capacity batteries as prime mover for electric vehicles and a backup storage cells for the power grid. In the V2G arrangement a car battery can be charged and discharged based on the active signal to incur electricity production or consumption[61]. Vehicle-to-grid enables the charging power to momentarily push back to the grid from electric car batteries to balance variations in energy production and consumption[335].

The vehicle-to-grid allows the power system to balance more and more renewable energy by deployment of renewable energy sources and introducing advanced energy storage. V2X turns EV charging from electrical demand response to a battery solution [35]. Electric vehicles are linked to the electricity grid to enable grid charging and discharge of batteries in the V2G arrangement hence the electric vehicles are referred to as grid connected EVs (GEVs) [12, 56]. The vehicles in the V2G arrangement have a plug-in feature equipped with a bidirectional charger that allows the battery to draw energy from the grid for charging and back to the grid during discharge battery and back[61].

Other potential products and services related to V2G concept depend on discharging and charging ability of the GEVs and grid efficient and energy needs are vehicle-to-home (V2H), vehicle-to vehicle (V2V). These technologies will enable the vehicle to act as a variable load and source of distributed electricity for the grid. Extensive research is done and is still ongoing to optimize the performance and cost of the V2X technology to make it technically and economically viable[56, 61].

By means of V2G technology, parked electric vehicles can be used as distributed sources of electricity with ability to store, and release energy at the time of need which allows power exchange between the electricity network and the Electric vehicle. The result is increased electricity generation capacity for the grid which improves stability, reliability, and efficiency the power system. The AC–DC Bidirectional electronic converters, namely (BADC) and DC–DC (BDC), are used to enable G2V and V2G interchange [550]. Converters facilitate high efficiency power conversion, and with progress in converter technology, EV charging stations assist in the transition to a green environment [550].

The V2G technology enables the EVs to be clustered via aggregator to offer grid power services like load leveling, voltage regulation, and peak shaving, at a lower cost and with less environmental impact. Therefore, smart grid technology deployment will enhance the operation and control of electric vehicles making them important energy transition facility[3, 56, 96].

18.2.3.2. Vehicle to House (V2H)

In many electricity markets, peak demand occurs between 5 p.m. and 11 p.m. for most grids, which is often a time when most private and public vehicles are parked at homes or stations. During this period, the vehicle to house (V2H) technology facilitates connection of parked vehicles to an electricity distribution board at home to meet demand peak demand [35]. During off peak hours, the same vehicle can be changed from vehicle to grid or vehicle to house to grid to vehicle connection to have the batteries charged preferable by power from intermittent sources like rooftop solar PV[550].

18.2.3.3. Vehicle to Vehicle (V2V) Technologies

The V2V or 'Vehicle-to-Vehicle' technology facilitate interchange between vehicles. Other than vehicles exchanging power or charging, sensors can also be applied to provide the car with data and information from other cars a few hundred meters ahead or even hidden cars. The normal or traditional V2V is done through an energy aggregator like in electrical power

grid, made of a combination of the vehicle-to-grid (V2G) and grid-to-vehicle (G2V) operation modes[3, 56, 96].

The normal V2V power transfer is based on four power conversions because each on-board electric vehicle battery charger has two power converters (dc-dc and dc-ac). Advanced form of V2V power transfer can take place in AC and DC power systems, focusing in the V2V power transfer using DC power (dcV2V). Modern V2V can discard an aggregator connection by directly connecting the EVs, charging one EV from the other which can reduce the four power conversions to one, hence higher overall efficiency in power transfer between electric vehicles [1033, 1034]. The V2V charging mechanism requires proper management of different expectations of EVs and reach the win-win situation for electric vehicles and the grid. [1034].

18.3. Opportunities and Challenges of the Transport Sector in Energy Transition

The electric vehicles have potential to reshape the transport and energy sector by reducing carbon emission and contribute to the realisation of the global climate targets. The life cycle emissions of electric cars is half or less than half of the emissions of comparable gasoline-powered vehicles[1035]. The electric vehicles (EVs) also emit carbon emissions through the manufacturing process and electricity generation process used to recharge. The average conversion efficiency of EVs is 77% of electrical energy from the grid to power at the wheels, compared to gasoline vehicles which generally convert between 12 to 30% of the energy in gasoline to power at the wheels[12, 61, 1035].

18.3.1.Challenges of Electric Vehicles

The main threat or obstacle in the electrification of transport is competition from traditional means of transport like fossil fuels, ethanol, gas, and others that are well established in several countries [14]. The traditional or conventional mode of transport remain cost competitive and convenient in terms of energy access. Notable challenges of electrification of transport include [35].

18.3.1.1. Long Charging Times

Electric vehicles have three major levels of chargers available for use in charging namely the standard 120-volt plug, mainly used for charging home appliances at slow rates but with the benefit of charging the battery to near full capacity over several nights or about 20 to 40 hours [35]. The second type of charger is the 240-volt "level two" chargers which can service

20 to 25 miles of charge in an hour, thus it shortens the time by eight hours or less. The level two chargers can use the same charge outlet with devices like the clothes dryers or electric ovens. The connectors for level two charging are known as SAE J1772 in the EV industry. The level 3 direct current (DC) fast chargers can fill the battery to about 80 percent in 30 minutes. Costs for level two charger's components vary from \$2,500 to \$7,210 while a DC fast charger vary from \$20,000 to \$35,800. [1035].

18.3.1.2. Charger Compatibility

Level two charger development is a relatively coordinated process, where all automakers except Tesla use a common charge port model. Tesla drivers on the other hand use an adapter to connect [35]. Three types of DC fast chargers used by auto manufacturers are the SAE Combined Charging System (CCS), CHAdeMO, used by Mitsubishi and Nissan the Tesla Supercharger used by Tesla drivers. Lack of vehicle compatibility from universal vehicle access to gas stations could be an obstacle to widespread adoption of electric vehicles [1035].

18.3.1.3. Availability of Charging Infrastructure

Most electric vehicles can travel between 150 and 250 miles on a charge, based on model. However, drivers who live in apartments may have parking that are not equipped with charging infrastructure which is an inconvenient[1035]. There is need for expanded charging infrastructure for EVs making long-distance trips that require multiple stops for charging. For longer trips, many EV owners experience range anxiety with fear that the car will run out of power away from a suitable charging station. Concerns about range and charging availability limit on consumer uptake of electric vehicles [61, 1035].

18.3.1.4. Grid capacity

With the electrification of transport, millions of people will rely on the electric grid in new ways which means that power generation capacity should increase to accommodate these millions of vehicles without straining the grid. The US Department of Energy foresees a 38 percent increase in electricity consumption by 2050 mainly due to largescale uptake of electric vehicles [35]. The grid ability to handle electric vehicles charging depends the time of charging the vehicles with lower chance of grid overload if it is done during off-peak hours [61, 1035].

18.3.1.5. Vehicle Costs

Electric cars use expensive materials and parts especially for making batteries making them generally more expensive than their fuel powered vehicles [35]. With new electric vehicle costing around \$30-40,000 although the prices have a falling trend over time [1035].

18.3.1.6. Charging Behaviour

The charging behaviour of electric cars differs significantly from the engine driven with about 80 percent of EV charging being done at home [35]. Many electric vehicle car owners are uneasy about the prospect of long charging times at public stations on long distance travel [1035]. Therefore, development of home charging should be promoted in addition to public charging for long distance travellers.

18.3.1.7. Sales Outlook.

The stock of electric vehicles market is growing, but dramatic increase is needed to meet the emissions and climate targets. In 2019 electric cars made up 2.1 percent of all new light-duty vehicle sales in the US up compared to 0.7 percent in 2015 with main players in the market being Tesla as the largest player in the US although Nissan Leaf has the largest share of used EV sales. Electric vehicles are expected to account for about 7% of all vehicles on the road by 2030, or about 18.7 million vehicles in the US. [1035].

18.3.1.8. Charging Station Financing and Ownership

Charging stations are expensive to install with, public station component costing generally from about \$2,500 for a level two charger to \$35,800 for a DC fast charger and these exclude installation costs and other costs like pursuing permitting process, regulations, and interconnection with utilities hence the legitimate question on who pays for the construction of these stations [1035].

18.3.1.9. Charging Pricing Inconsistency

EV charging applies different pricing schemes unlike the conventional ones where fuel pricing is common. This can lead to inconsistent pricing and at times high charging costs. Home charging prices are expressed in kilowatt-hour (kWh) and are set by utility companies [35]. Public charging stations charge per-session fees, per-minute, and tiered pricing based on a vehicle's max charging speed. The inconsistency and lack of transparency limit the adoption of electric vehicles due to frustration and negative customer experiences. Many

states allow per-kWh pricing, and in some cases with a tiered pricing structure, charging higher rates for faster charging speeds. [1035].

18.3.1.10. Legislation

Legislation is one of the factors limiting electric vehicle e.g. employees benefit in some states or countries only recognise fuel not electric vehicle charging which limits wide spread use of EVs. In the US, the Electric Vehicle Freedom Act, or EV Freedom Act (H.R. 5770), intends to construct electric vehicle supply equipment along all public roads in the National Highway for EV drivers to travel anywhere on these roads in the continental United States, Alaska, Hawaii, and Puerto Rico without running out of charge [35].

18.4. Behavior and Transport Sector Emissions

There is significant evidence that behaviour change has a key role to play in decarbonising the transport sector [35]. Demand-side measures can reduce kilometres travelled or, shift to less carbon intensive modes of transport. Scenario that relies on shifts in human activity patterns, preferences and price signals have far reaching implications other aspects of the economy and society e.g. wider consumption practices like leisure, food consumption and work practices, preferences for residential and business location and knock-on land values [1035].

18.5. Results and Discussion

The transportation sector is among the rapidly growing energy intensive sectors globally making it a leading contributor to global greenhouse gas emissions. Electrifying the transport promise to be a sustainable solution to reduce emissions.[56].Studies have shown that on average across the globe, electric vehicles account for 31% of emissions savings per kilometre, while heat pumps can save 35% in emissions per unit heating unit heating. Even where the grid is not quite clean, electrification of transport presents substantial emissions savings for most countries while huge savings are realized if effort to decarbonize the grid is made[1036].

The transport sector accounts for about 25% of global carbon dioxide (CO₂) emissions while the road sector accounts for close to 70% of the transport emissions [1037]. Electrification of transport and use of renewable fuels would reduce the ecological footprint, minimise anthropogenic emissions, and contribute towards greenhouse gas emissions mitigation[1037]. In the search for low-emission by nations, transport a sector that has

significant reduction potential and should therefore be a priority in realisation of Paris agreement targets[1038].

The transport sector which provides mobility for freight and people is a significant energy consumer accounting about 25% of global energy consumption [335]. The transport sector accounts for more 50% of the petroleum oil used and about 25% of global energy related (CO₂) emissions. Based on the year 2005 baseline, the transport energy consumption and related CO₂ emissions are expected to grow by more than 50% by the year 2030 and more than double by the year 2050 [1028]. The transport sector is a leading contributor to greenhouse gas emissions and measures must be put in place to reduce these emissions[3, 21]. Measures being undertaken in the energy sector include development of alternative electric and/or hydrogen powertrains and replacement of the hydrocarbon fuels and internal combustion engine (ICE) designs.[342].

The electrification of road transport features prominently policy frameworks of many countries as a strategy to reduce greenhouse gas emissions. The main challenge is that fossil fuels continue to dominate the electricity generation mix posing a challenge to the role of electric cars in effectively reducing overall emissions hence the need to rapidly decarbonize the grid electricity mix[35]. Studies however indicate that the current carbon intensities of electricity generation are less emission intensive than the electric cars and heat pumps in many global economies which account for close to 95% of the global transport and heating demand. Therefore even if future end-use electrification is not matched by rapid power-sector decarbonization, electrification of road transport will still reduce global greenhouse gas emissions[1036].

18.6. Energy/Technology Options for the Transport Sector

The basic energy sources and technologies used by vehicles are biofuels, natural gas and biomethane, hydrogen, electricity, and hybrid technology. These systems are analysed in Table 18-1.

Table 18-1: Energy systems and technologies for vehicle [35]

	Description	Remarks
1 Biofuels	Biofuels are renewable sources like ethanol, methanol, and biodiesel	The main challenge of biofuels is that they compete with food

		produced by fermentation biomass like sugar cane, corn, cereals, first-generation and second-generation biofuel	applications like sugar production, etc.
2	Natural gas	Natural gas is preferred for large fleets of vehicles with extensive travel like public transit buses or delivery trucks.	Natural gas is the cleanest fossil fuel and is easily substituted by renewable biomethane and can substitute diesel and petrol to reduce emissions
3	Biomethane	Biomethane is enriched biogas having similar properties with natural gas	Biomethane is regarded as renewable natural gas if the source of biogas is renewable.
3	Hydrogen	Hydrogen is generally used as a fuel for fuel cells used as prime movers for propulsion or generation of electricity to propel the vehicle. Most hydrogen is produced from fossil fuels i.e. natural gas	Hydrogen production is energy intensive and expensive. Storage challenges due to pressure and expensive materials and is sustainable if green hydrogen is used
4	Electricity	A pure electric vehicle is a more efficient alternative to an engine propelled vehicle.	Limited by energy storage capacity and service distance of the charge. It a more sustainable energy option if electricity is from clean and renewable sources
5	Hybrid	These vehicles consist of a propulsion system that uses an internal combustion engine supplemented by an electric motor and batteries	A hybrid car combines the efficiency of electricity with the benefit of long driving range of an internal combustion engine but expensive. Biofuels and renewable fuels can be used to increase sustainability

From Table 18-1, it is noted that various energy systems and technologies are available with different strengths and opportunities. The application and objectives will influence the best

choice as the global shift to net zero emissions take shape. Electric vehicles compete against conventional engines and energy systems., both renewable (biofuels, biomethane and hydrogen based on source) and non-renewable i.e. diesel, petrol, and natural gas.

18.6.1. Performance Analysis of Transports Drive Options

The various drive systems for vehicle are internal combustion engines, pure electric drives, fuel cells and hydrogen internal combustion engines. Table 18-2 shows the conversion efficiencies of internal combustion engines, pure electric vehicles, fuel cell vehicles and hydrogen internal combustion engines.

Table 18-2: Efficiency of vehicle energy conversion systems [35]

	Option	Conversion efficiency (%)	Rank
1	Internal combustion engine	12.7	4
2	Pure electric vehicles	51.6	1
3	Fuel cell vehicles (FCVs)	28.3	2
4	Hydrogen ICE (HICE) vehicles	26.6	3

From Table 18-2, it is noted that electric vehicles have the highest conversion efficiency, followed by fuel cell, hydrogen, and internal combustion engines in reducing efficiencies. Therefore, the internal combustion engine has the lowest conversion efficiency compared to other available drive systems.

18.6.2. V2X Options

Application of electricity in transport include use of plug-in hybrid EVs (PHEVs), battery EVs (BEVs), and fuel-cell EVs (FCEVs). The PHEVs use both diesel/gasoline and electricity and. Challenges facing electrical transport include the threat to grid stability from simultaneously charging of thousands of EVs. Technological advances that support electric vehicles include battery technologies like nickel-metal hydride (Ni-MH) and lithium-ion (Li-Ion), intelligent energy management systems, and vehicle-to-grid (V2G) technology. Compared with plug-in EVs, FCEVs generate electricity by refilling with fuels like hydrogen, alcohols or ethers instead of battery recharging [15, 16]. The performance of FCEVs is limited by storage system technology e.g. how to store hydrogen in the vehicle, and related high cost of energy storage and fuel cells limits commercial deployment[339], [1039].

There are several V2X technologies available for electric cars. They include Vehicle to grid (V2G), grid to vehicle(G2V), vehicle to house) V2H) and vehicle to vehicle (V2V). The options are summarised in Table 18-3.

Table 18-3: V2X systems [35]

	Technology	Description	Application
1	V2G and G2V	Vehicle-to-grid, or V2G, technology is a smart charging technology enable cars to supply power to the grid These vehicles have a plug-in feature equipped with a bidirectional charger enabling the battery to draw energy from the grid to the battery and back. The role can be reversed depending on need	In V2G technology, parked electric vehicles are used as distributed sources of electricity with ability to store, and release energy at the time of need
3	V2H	The vehicle to house (V2H) technology facilitates connection of parked vehicles to an electricity distribution board of home to meet demand peak demand. During off peak hours, the same vehicle can be charged later from vehicle to grid or vehicle to house to grid	The technology can be used to supply power when the grid power is expensive or is not available. The system can also utilize intermittent sources like rooftop solar PV and wind for later use
4	V2V	The normal V2V power transfer is based on four power conversions because each on-board electric vehicle battery charger has two power converters (de-de and dc-ac). In advanced form V2V power transfer, can take place in ac and dc, focusing in the V2V power transfer using dc power (dcV2V).	Modern V2V can discard an aggregator connection by directly connecting the EVs, charging one EV from the other at higher efficiency

From Table 18-3, it is observed that the V2X technologies are V2G, G2V, V2H, V2V. These technologies enable the electric cars to play a grid role not just as power consumers, but as decentralised power sources as well. The electric vehicle can therefore be used to stabilise the grid and be a source of grid power to the power grid.

18.6.3.Challenges/Limitations of Electric Vehicles

Many factors limit the rapid deployment of electric vehicle globally and should be addressed for faster adoption of the electric transport. These limitations are summarised in Table 18-4.

Table 18-4: Limitations of electric cars [35]

	Limitations	Remarks and recommendations
1	Charging time	Electric vehicles have three major levels of chargers available for use in charging with charging time ranging from few days for 120-volt plug chargers to 30 minutes by the level 3 direct current (DC) fast chargers. The higher the Level, the higher the charger power output and the faster it can charge the battery.
2	Charger compatibility	They are the SAE Combined Charging System (CCS), CHAdeMO, used by Mitsubishi and Nissan the Tesla Supercharger used by Tesla drivers. Lack of vehicle compatibility from universal vehicle access to gas stations could be an obstacle to widespread adoption of electric vehicles
3	Charging infrastructure	There is need for expanded charging infrastructure for EVs with concerns about range and charging availability limiting on consumer uptake of electric vehicles
4	Grid capacity	Electrification of transport implies that millions of people will rely on the electric grid to charge their cars hence the risk to grid stability
5	Vehicle costs	Electric cars use expensive materials especially for battery parts making them generally more expensive than their fuel powered vehicles.
6	Charging behaviour	About 80 percent of EV charging is done at home unlike the conventional engine cars which fuel in gas stations
7	Sales outlook	The stock of electric vehicles market is growing fast, but the market share remains low hence need to increase to meet the emissions and climate targets.
8	Charging station financing and	Charging stations are expensive which raises the legitimate question of who pays for the public charging stations.

	ownership	Governments can sponsor initial public charging stations
9	Pricing	EV charging applies different pricing schemes leading to inconsistent pricing and at times high charging costs
10	Legislation	Legislation is one of the factors limiting electric vehicle adaptation hence the need to develop a legislative and policy framework to encourage use of electric cars

From Table 18-4, it is noted that electric vehicles still encounter numerous shortcomings compared to the conventional engine driven cars. They include lack of supporting legislation, low sales volumes, lack of standardization like charger incompatibility, inadequate grid capacity to handle the many electric vehicles and concerns over ownership and financing of public charging infrastructure [35].

Electrification of transport is a potential panacea to many countries facing vehicular pollution. However, we could have a scenario where emissions may rise if electric vehicles depend upon energy generated from non-renewable sources like coal. Several studies have shown the electric vehicles would indirectly emit more CO₂, NO_x, and SO₂ if power is from fossil fuels like coal. However, the CO emissions from vehicles will significantly reduce compared to conventional vehicles[1040].

18.7. Conclusion

The electric vehicles have significant potential to reshape the transport sector by reducing carbon emission and contribute to the realisation of the global emissions and climate targets. The life cycle emissions of electric cars are half or less than half of the emissions of comparable gasoline-powered vehicles. The electric vehicles market is widespread with vehicles ranging from electric bikes to airplanes. Electric powered passenger cars have received the widest attention and hold an important position in the energy transition. The main drivers of the electric vehicle markets are government incentives, environmental awareness and concerns, high fuel prices, phasing off government subsidies for fossil fuels.

The main challenges facing the electric vehicle industry are limited range and slow charging times, high cost of EVs, and inadequacy of charging infrastructure to support the electric vehicles industry, gain wider acceptance and realise rapid deployment. Nevertheless, the EV industry is growing significantly across the globe, particularly with advancement in battery technologies particularly the all-solid-state batteries with reduced charging time, increasing range, and reduced manufacturing costs.

Although hybrid, Plug in Hybrid and Electric Vehicles are expensive compared to the traditional vehicles, they have higher fuel economy. V2X technologies are V2G, G2V, V2H, V2V. These technologies enable the electric cars to play a grid role not just as power consumers, but as decentralised power sources as well. The electric vehicle can therefore be used to stabilise the grid and be a source of grid power to the power grid. The concept of Vehicle-to-Grid (V2G) and Grid –to-Vehicle (G2V) can be used to either deliver power to the grid or use the grid to charge the battery in the absence of non-conventional energy sources. V2G is an important aspect of energy security, renewable energy, and hence an important tool against global warming issues.

The introduction of electric and hybrid passenger cars, and use of ethanol as a fuel, will help cities in their effort to mitigate the greenhouse gas (GHG) emissions by reducing the consumption of fossil fuels. Studies show that emissions from electric vehicles (EV) are significantly less than ethanol if the wheel to wheel (WTW) approach for CO₂ emissions estimation is applied. Projections show that with increase of electric and hybrid vehicles, the transport sector will consume close to 10% of electricity. Charging of many electric vehicles needs meticulous monitoring to avoid a surge of peak loading on the electricity infrastructure. Smart grid and microgrid technology can facilitate prioritization of charging in cases of low demand exploiting the use of both low-cost generation and extra system capacity.

18.8. Recommendation

It is important to couple the energy sector with transport sector through electrification so that green electricity can be used to power vehicles and reduce the transport sector derived greenhouse gas emissions. On the other hand, with V2G technology and hybrid vehicles, green and renewable fuels like hydrogen, biodiesel, bioethanol, biogas and biomethane, and natural gas as a cleaner fossil fuel can drive and charge vehicles for later use to supply power to the grid.

CHAPTER 19:

SUSTAINABILITY ASSESSMENT OF ENERGY SOURCES

19. Overview

In this chapter, key energy resources, and their sustainability are presented. The contents of this chapter are published in papers referenced as [22, 23, 29, 32, 39, 181, 853, 1020]. Energy plans model is used to test the effect of various energy sources to supply a specified amount of electricity in terms of cost, emissions, and social impacts. There is a need for energy solutions that simultaneously address the developmental issues related to the environment, economic growth, and social equity needed by societies. Renewable and sustainable sources face major barriers that limit largescale implementation but their friendliness to the environment make them widely acceptable. For largescale adoption, and uptake of renewable sources, the power grid is undergoing modernization to become efficient, resilient, and reliable by replacing or upgrading the traditional grid with the smart grid.

Renewable energy has a very important role to play in sustainable power generation to promote sustainability of environmental sustainability in power generation. Over 60% of global electricity generation is derived from fossil fuel sources mainly coal, and natural gas which is unsustainable. Energy is a leading contributor to the climate change, and accounts for about 60% of global GHG emissions. As an emission reduction strategy, renewable energy (RE) generation and integration has been accelerated globally. The wider adoption of renewable energy generation is associated with both positive and negative impacts. It also encounters several economic, social, technical, political, and environmental challenges. To attain sustainable power systems, focus should be placed on key areas like energy efficiency and diversity, social value and public acceptance, power supply reliability, technological innovation, competitive and cost reflective pricing, market-sensitive interventions, standard requirements, regional integration, and power quality. Successful energy transition requires progress in these areas.

There are various indicators used to assess power generation technologies. They include price of generated electricity, full lifecycle greenhouse gas emissions, availability of renewable sources, energy conversion efficiency, land use requirements, water consumption and social and economic impacts. The cost of electricity, greenhouse gas emissions and the efficiency of electricity generation have a wide range for each technology option because of wide range of

available technology options and varied geographical dependence. The social impacts of energy sources are qualitatively based on the major individual impacts from literature. Renewable energy technologies were then ranked against each indicator assuming that indicators have equal importance for sustainable development. The study showed that renewable energy resources have sufficient potential to achieve a sustainable electricity system. The study shows that wind power is the most sustainable, followed by hydropower, photovoltaic and then geothermal energy sources. However, wind has got higher land requirements and relatively higher cost of generation.

19.1. Introduction to Energy Sources for the Energy Transition

There are various energy sources used in heat and power generation through different conversion systems. They are summarised in Table 19-1.

Table 19-1: Summary of energy options for the global transition

	Energy resource	Features and composition sustainability	Contribution to the transition and sustainability
1	Hydropower	Hydropower is renewable and is gotten from moving water which runs hydraulic turbines. Hydropower is affected by weather	Hydro has contributed clean power for many years. Significant potential remains in small and mini hydropower schemes in decentralized and centralized generation.
2	Solar Energy	Solar is a variable renewable energy supplied by natural radiations from the sun. the energy is affected by weather and may be unpredictable intermittent in some cases	Solar will play a big role in the future transition as a renewable energy resource but development in solar cells technology and smart grids will enhance their uptake contribution to grid electricity. Energy storage and transition to smart grids will enhance their use in electricity generation
3	Wind Energy	Wind is natural and renewable and can be	Wind resources are significant but variable in supply. Their huge

		developed as onshore or offshore wind power stations. The main challenge facing wind power is variability and intermittent as well as large land requirements.	contributions lie in the transition to smart grids and development of energy storage facilities. Wind power is clean and abundant although variable and intermittent. Smart grids and energy storage will improve their uptake and contribution.
4	Hydrogen	Hydrogen can be made by electrolysis and mainly by steam methane reforming	Hydrogen will play a leading role in development of fuel cells and as a fuel to replace fossil fuels. More research into efficient conversion and handling is needed to generate hydrogen from renewable sources as opposed to use of fossil fuel gases.
5	Biogas	Include biogas, biofuels, energy crops, plant waste, animal waste. Relevant policy measures necessary to make them competitive	Renewable and zero and low carbon sources and can substitute fossil fuels domestic, industrial, transport and power generation. Bioenergy sources include biogas, syngas, gasification, bagasse, bioethanol, biodiesel and other fuels and energy sources of organic origin including energy crops.
6	Biomethane	Biomethane can be made by upgrading biogas or syngas	Can replace natural gas in almost all applications
7	Biodiesel	Made from biomass as a renewable energy resource	Can be used as a substitute of fossil fuels in transport and power generation.
8	Bagasse	Bagasse is green energy which is a solid byproduct of sugar cane milling	Can be used for heat and power generation by sugarcane factories. Bagasse can also be used to produce bioethanol which is an energy resource
9	Solid	Biomass can be obtained	Biomass can be used in power plants

	Biomass	as waste products, forest products or energy crops	for heat and power generation.
10	Geothermal Energy	Geothermal energy has significant potential but huge upfront costs, investment risks and long project delivery tools have kept contribution low	Geothermal has very low actual and lifetime emissions. Has high load factors and capacity factors and hence ideal for base load electricity supply, Increased use of geothermal will reduce electricity price, reliability and cut greenhouse gas emissions. Use of wellhead generators can help mitigate some shortcomings like cost and project duration.
11	Producer gas	Huge quantiles of animals, plants, and combustible industrial wastes most with significant energy potential are produced continuously globally. They include municipal solid waste, agricultural waste, and animal waste like slaughterhouse waste	Various waste to energy technologies exists with more efficient systems being needed for efficient waste to energy conversion. Processes like biogas and biomethane production, direct combustion can be used both for a clean environment, generate green energy and electricity and reduce disposal costs and health risks in a sustainable manner.
12	Nuclear energy	Nuclear power takes many years to develop, guarantees a large supply of low carbon electricity at high load factor and capacity factor. Also, unit cost of power is relatively low.	Nuclear will increase reliability, reduce unit cost of power, and cut emissions. There is a need to increase funding for nuclear energy and reduce the high project duration. Use of small modular reactors for countries with low demand and to facilitate phased development is encouraged for

			faster growth of nuclear power.
13	Ocean /marine energy	This is a renewable energy resource mainly in the form of tidal power, wave power, osmotic and ocean thermal. Ocean thermal is limited by the low thermal gradient over which heat transfer is to take place.	Marine energy has very limited contribution globally by will lay a leading role in the transition by investing in efficient technology for extraction of energy with low thermal gradient in ocean thermal. Policy incentives and funding are necessary to increase generation from wave and tidal power. The main challenge with marine power is that supply is not continuous, but relatively predictable.
14	Natural gas	Natural gas is nonrenewable source but cleaner than coal, diesel and petrol and global resources are huge	Can substitute heavy polluters like coal and petroleum like diesel and petrol as fuel. The main challenge is delay in the transition to zero carbon target and investment risk involved with the transition.
15	Coal	Coal is nonrenewable and currently the largest source of global electricity. Huge reserves in some countries.	Coal produces reliable power but has high emissions. It can stabilize generations. Consumption should gradually be reduced by substitution. However, coal generate ash and carbon dioxide, N ₂ O and SO ₂ hence high environmental impact
16	Oil	Generate high carbon emissions as well as N ₂ O and SO ₂ . High reserves in some countries hence slow transition	With application of efficient generation like cogeneration and blending, can supply limited power and fuel for use

From Table 19-1, it is noted that both renewable and nonrenewable sources of energy have a role to play in the energy transition. Nonrenewable sources like coal and oil are abundant in

several countries and therefore are readily available and offer energy security. The steady release of energy by fossil fuel sources is important for reliability and stability and hence quality which are sustainable energy requirements. However, their high carbon footprint, finite supply, price and supply interruptions and resource related conflicts make fossil fuels unreliable and unsustainable source of energy and hence the need for gradual substitution with renewable and low carbon sources of energy. The use of highly efficient conversion technology and clean coal as well as carbon capture and sequestration can greatly reduce the carbon footprint of fossil fuel sources. For natural gas, controlling leakages along the entire supply chain is paramount due to the high global warming potential of methane which is the main constituent of natural gas. Solar and wind offer the greatest potential but suffer from unpredictable and unreliable supply challenges, hence the need for advanced energy storage facilities. For grid electricity, the unreliability and unpredictable supply nature of wind and solar is a danger to energy security and the grid stability for the traditional grid. However, the use of smart grids with ability to absorb small scale producers and variable supply will greatly increase the absorption of wind and solar energy as well as small hydro sources and decentralized generation.

19.2. Technical Indicators of Energy Sustainability Assessments

19.2.1. Energy Density of Combustible Energy Sources

Energy density is an important aspect of energy management and hence sustainability since it influences the design of the energy conversion system in terms of size, material handling and overall efficiency and cost. Table 19-2 shows the energy density of different energy sources.

Table 19-2: Energy density of energy sources

	Energy source	Range	Average (MJ/kg)	Rank
1	Uranium 235		79,390,000	3
2	U-238/Pu-239		80,620,000	1
3	Th-232/U-233		79,420,000	2
4	Coal	24-30	32	8
5	Oil		42	7

6	Natural gas		53.5	5
7	Hydrogen		120	4
8	Biomethane		53.5	5
9	Biogas (1.2 to 1.5 kg/m ³)	14-15.7	14.9	9
10	Bagasse at 50% moisture content		9.6	11
11	Wood (biomass)		16.2	10

From Table 19-2, it is noted that nuclear energy sources i.e. Uranium 235, U-238/Pu-239, and Th-232/U-233 have the highest energy density while bagasse has the lowest energy density due to high moisture content. Hydrogen has the highest energy content among the combustible fuels considered followed by natural gas and biomethane. Biogas has lower energy content due to high volume of non-combustible carbon dioxide while moisture in wood biomass significantly reduces its energy content.

19.2.2. Energy Resource Availability

The sustainability of energy sources can be assessed on resources availability, locally and globally. Table 19-3 indicates the estimated resource potential and availability for exploitation in energy applications.

Table 19-3: Energy resource availability [1041]

	Energy resource	Global potential/availability	Remarks
1	Hydropower	13,000 TW h	Global potential
2	Solar Energy	170,000 TW h.	Global potential
3	Wind Energy	40,000 TW h	Global potential
4	Hydrogen	19 EJ	Potential contribution by 2050
5	Biogas	1.46 EJ	Global production capacity

6	Biomethane	3.5 Mtoe	<i>of biomethane are produced worldwide</i>
7	Biodiesel		
8	Bagasse	600 million tons of bagasse/year	25-30 percent of cane milled is bagasse
9	Solid Biomass	3.6 TWh/year	
10	Geothermal Energy	87.6 TWh/year	
11	Nuclear energy	2.87 million tons (Uranium and thorium)	
12	Wave energy	7.5 kW/m of sea front	
13	Tidal power	8000 TW h	
14	Ocean thermal	2000 TWh	
15	Ocean osmotic	2000 TWh	
16	Natural gas	6,922,922,000 million Cubic Ft (MMcf)	
17	Coal	1,074,108 million metric tons	Available in 2023
18	oil	1,754.6 billion bbl,	Available by 2023
19	Hydrogen	95 Mt /year	Global demand

From Table 19-3, it is noted that the potential energy production estimates for these innovative technologies are approximately 800 TW h for tidal energy, 2000 TW h for ocean osmotic energy, and somewhere between 8000 and 80,000 TW h for wave energy.

19.3. Environmental Indicators

19.3.1. Gaseous emissions

Several environmental indicators can be used in sustainability assessment of energy sources. Table 19-4 shows the environmental indicators in terms of various emissions.

Table 19-4: Environmental indicators

Resource	CO ₂ (g/kWh)	NO _x (g/kWh)	SO ₂ (g/kWh)	CH ₄ (g/GJ)
Hydro	2–20	0.004–0.06	0.001–0.03	-
PV	49.174	0.178	0.257	-
CSV	13 –19	0.054–0.082	0.035– 0.049	-
Wind	3 – 41	0.02–0.11	0.02–0.09	-
Geothermal	18.913	0.28	0.02	-
Biomass	8.5–130	0.08–1.7	0.03–0.94	40
Oil	530– 900	0.5–1.5	0.85–8	8
Coal	660–050	0.3–3.9	0.03–6.7	5.5

From Table 19-4, it is noted that coal has the highest emissions in terms of CO₂, NO_x and CH₄, while wind and hydro have the lowest.

19.3.2. Life Cycle Emissions

Detailed studies have shown that the average greenhouse gas emissions for renewable energy derived electricity production varies between 34 and 50 g CO₂-eq./kWh for wind and solar PV, respectively, 20–80 g CO₂-eq./kWh for concentrated solar power, and 40–80 g CO₂-eq./kWh for geothermal[1042]. The average lifecycle emissions from various sources are presented in Table 19-5.

Table 19-5: Life cycle emissions and ranking for various conversion technologies [1042, 1043]

	Energy	Energy Source Conversion	gCO ₂ eq/kWh	Rank
1	Coal	PC without CCS	1000	28
2	Coal	IGCC, without CCS	850	26
3	Coal	SC without CCS	950	27
4	Coal	PC with CCS	370	23
5	Coal	IGCC with CCS	280	21
6	Coal	SC, with CCS	330	22
7	Oil	Oil	840	25
8	Natural gas	NGCC, without CCS	430	24
9	Natural gas	NGCC, with CCS	130	19
10	Hydro (large)	660 MW	150	20
11	Hydro (small)	330 MW	11	4
12	Pumped hydro storage		7.4	2
13	Nuclear	Nuclear power plants	5.1	1
14	CSP (concentrated solar power)	Tower	22	12
15	CSP	Trough	42	17
16	PV (solar photovoltaic)	poly-Si, ground-mounted	37	14
17	PV	poly-Si, roof-mounted	37	14
18	PV	CdTe, ground-mounted	12	6
19	PV	CdTe, roof-mounted	15	11
20		CIGS, ground-mounted	11	4

21		CIGS, roof-mounted	14	9
22	Wind	Onshore	12	6
23	Wind	Offshore, concrete foundation	14	9
24	Wind	Offshore, steel foundation	13	8
25	Ocean energy	Ocean thermal, tidal and wave	8	3
26	Biomass energy		52	18
27	Lithium-ion storage		33	13
28	Hydrogen fuel		38	16

From Table 19-5 , it is noted that the lifecycle emissions various widely from one energy resource to another, from one technology to another and other factors. Therefore, planners should carefully select the energy sources and the technology within the same energy sources for best results and choices for planning of generation, both in long term and real time deployment of power plants.

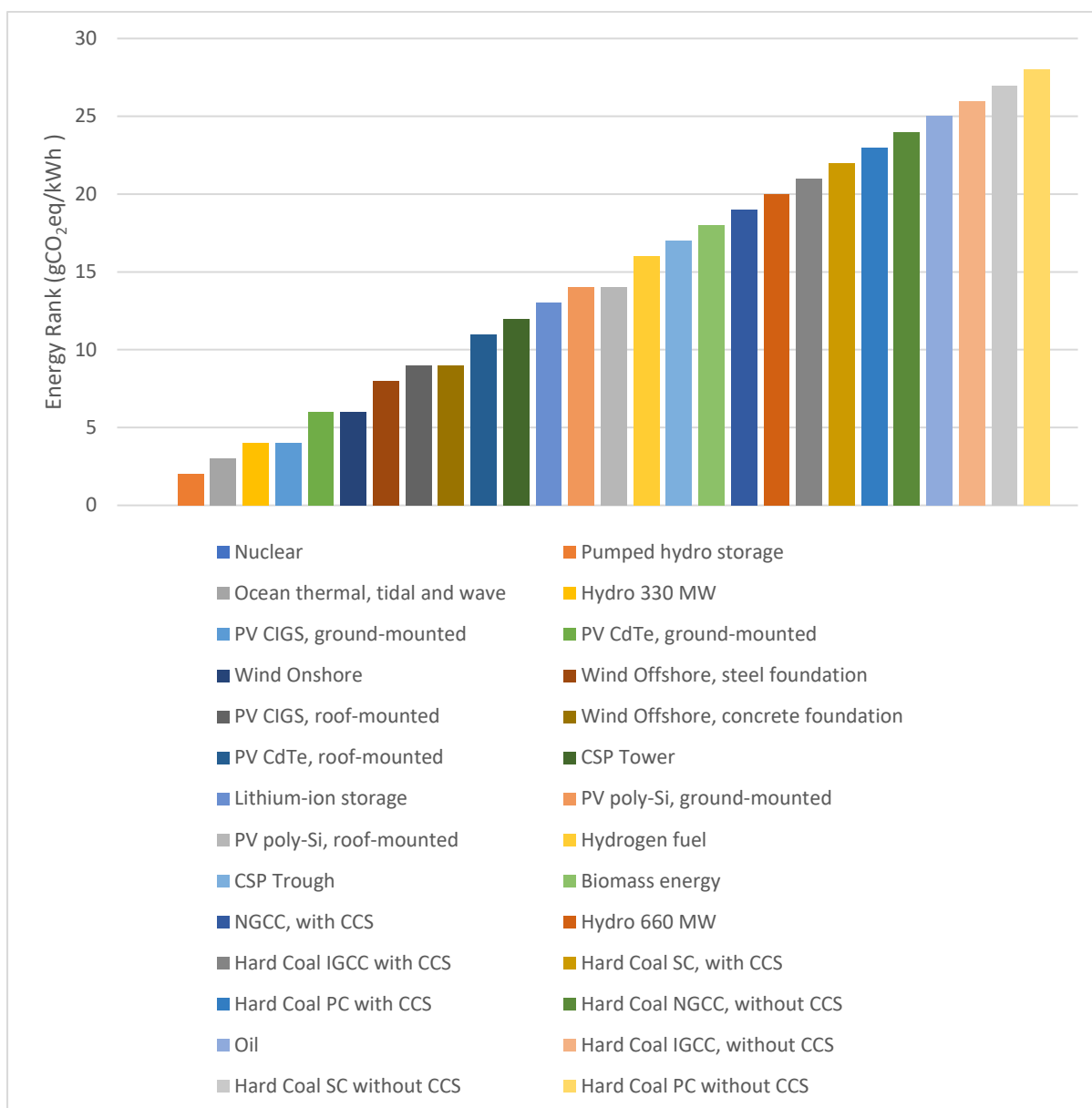


Figure 19-1: Lifecycle emissions of different energy sources

From Figure 19-1, the PC without CCS has the highest life cycle emissions followed by SC without CCS. The technologies and energy sources with lowest life cycle emissions based on the analysis are nuclear followed by pumped hydro storage and ocean energy. electricity generation technologies arranged in decreasing order based on the median (gCO₂eq/kWh) values. Wind onshore technology has the least average life cycle emissions followed by nuclear and offshore wind conversion systems. Coal PC without CCS has the highest lifecycle emissions.

19.4. Economic Indicators of Sustainability[1044].

19.4.1. Energy Resource Price

The price of energy is an important factor in sustainability as it affects the price of electricity and the demand. Various factors affect the price including availability and taxes imposed by the state e.g. carbon tax. The price of an energy resource is what is paid for acquisition and is usually based on prevailing market price.

Table 19-6: Energy resource price

	Energy resource	Market Price Range (USD)	Average
1	Hydropower	0	0
2	Solar Energy	0	0
3	Wind Energy	0	0
4	Hydrogen	0.5-8.5/kg	4.5/kg
5	Biogas	2-20 2/MBtu	11/ MBtu
6	Solid biomass	44-85/tone	64.5/tone
6	Biomethane	0.45—0.75/LGE	0.6/LGE
7	Biodiesel	50-69/litre	54.5/litre
8	Bagasse	9-22	10.5/MT
10	Producer gas	6.5 per mmBtu	6.5 per mmBtu
11	Uranium	120-130 /kg	225/kg
12	Wave energy	N/a	
13	Tidal power	N/a	
15	Natural gas	2.63- 2.78/MMBtu	2.705 MMBtu
16	Coal	130-137.14 /kg	133.6/kg
17	Heavy Fuel Oil	0.6-0.644 /kg	0.622/kg

18	Diesel	1.20-1.25/litre	1.225/liter
19	Petrol	1.25-1.30/liter	1.275/liter

From Table 19-6, it is noted that the price of energy resources varies with type of energy, while factors like quality and other costs like freight affect the price of the same energy resource.

Table 19.6. Levelized cost of Energy

	Energy resource	Levelized cost of energy (USD)/MWh	Average USD/MWh
1	Hydropower	50-70	60
2	Solar PV-Utility scale	49-185	117
	Solar PV-Roof top	117-282	199.5
3	Wind Energy-Onshore	33-35	34
4	Wind power-Offshore	79 - 81	80
5	Nuclear	141- 221	181.5
6	Coal	68-166	117
7	Combined cycle natural gas turbines	39-101	70
8	Bagasse	9-22	15.5
9	Hydrogen fuel cells	278 - 322	300
10	Battery energy storage	270-442	356
11	Biogas systems	50-190	120
12	Solid biomass	40.5 -46.3\$	43.4
13	Biomethane	80-200	140

14	Magnetohydrodynamic generation	212.2 - 218.9	215.6
15	Geotherma lenergy	40-140	90
16	Diesel power plants	300-500	400

The levelised cost of the various energy and power sources presented in table 19..2 can be diaagramatically presented in figure 19.2 below

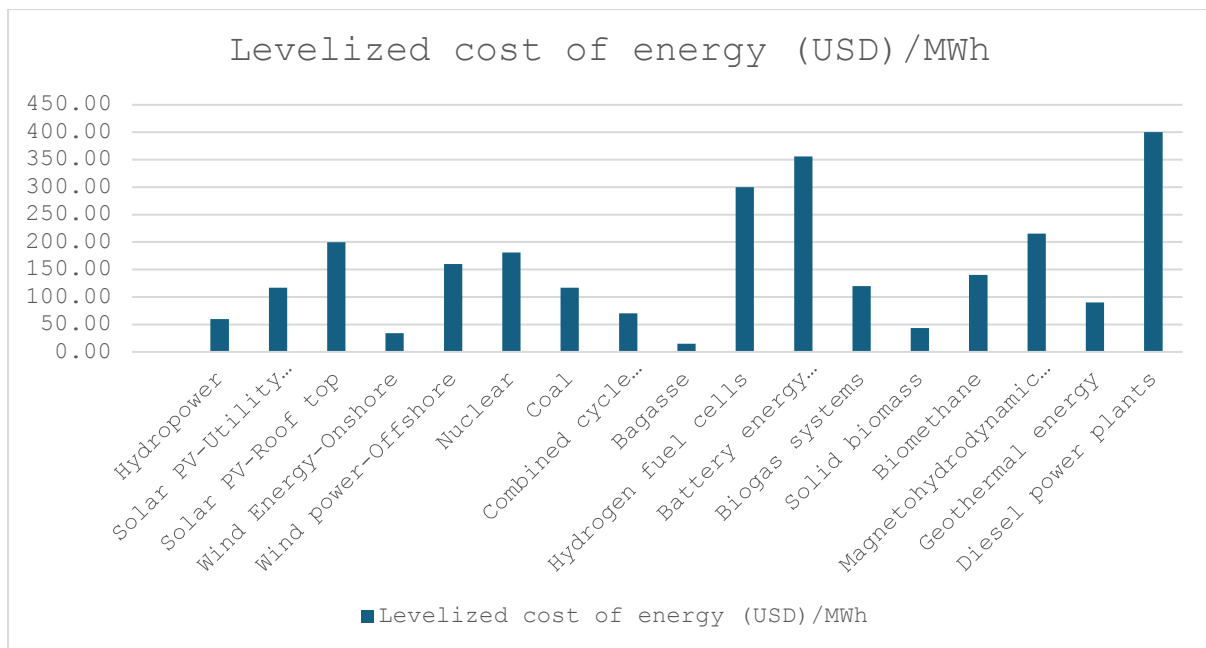


Figure 19.2: Levelised cost of energy from different sources

From figure 19.2 and table 19.6.2, it is observed that diesel power generation, battery energy storage and hydrogen fuel cells have the highest values of levelised cost, while bagasse, offshore wind and solid biomass have the lowest levelised cost of energy.

19.5. Social Factors and Sustainability

The social effects of energy sources are significant sustainability indicators of the energy resources. Energy use for power generation creates effects on the social life of societies directly and indirectly like negative health effects, causing air pollution and global warming. Other effects are external costs like accidents which create negative approval from the public on various technologies[1045]. There are many social indicators for social sustainability analysis like corruption index (CI), employment creation, intergenerational issues, measured as human toxicity (HT) and abiotic depletion (ADP and local community impacts measured

as corruption index (CI) [1046]. Important social factors considered in the selection of energy sources include job creation, safety risk in terms of fatalities and a measure of social acceptance.

Table 19-7: Social effects of energy sources

Resource	Job creation (Total job-years/GWh	Safety Fatalities/GWeyr	risks	Social acceptability (%)
Hydro	0.27	0.945		68
PV	0.87	0.000245		94
CSV	0.23	0.000245		94
Wind	0.17	0.00189		69
Geothermal	0.25	0.00174		56
Biomass	0.21	0.0149		56
Natural gas	0.11	1.69		30
Oil	0.11	1.08		32

From Table 19-7, it is noted that solar PV has the highest positive social effect in terms of job creation while fossil fuels i.e. natural gas and oil has the lowest. In terms of safety measured by fatalities, fossil fuels i.e. oil and gas have the highest negative impact while geothermal and wind which are non-combustible renewables have the lowest fatalities, hence the safest.

The social effects of different energy sources in power generation are presented diagrammatically in figures 19.3, 19.4 and 19.5

19.5.1. Social acceptability of energy sources for power generation

The society degree of acceptance for different energy sources varies as demonstrated in figure 19.3.

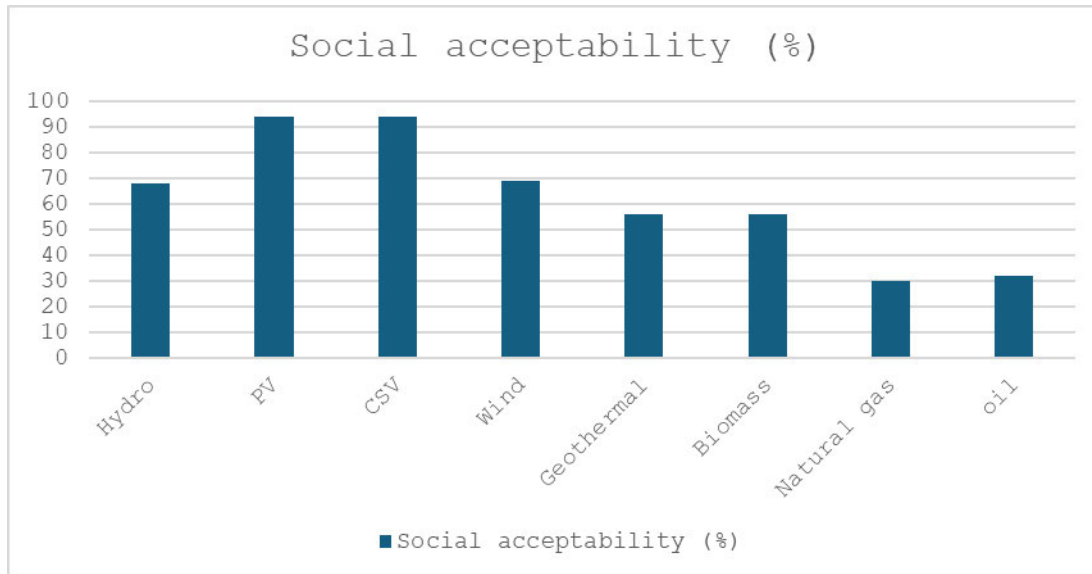


Figure 19.3: Social acceptability of different energy sources

From figure 19.3, it is noted that solar energy is the most acceptable source of for power generation followed by wind and solar , while the least acceptable sources are natural gas and oil which are both fossil fuels.

19.5.2. Job creation potential by energy sources

Different energy sources have varying degree in job creation potential as demonstrated in figure 19.4 below.

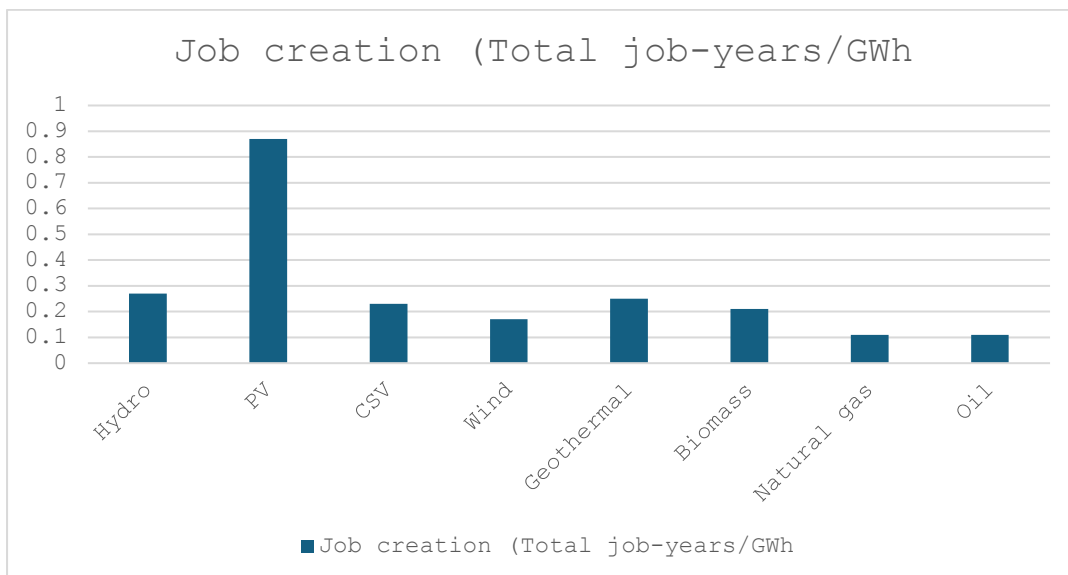


Figure 19.4: Job creation potential of energy sources for power generation

From figure 19.4, it is noted that solar PV has the highest job creation potential followed by hydro and geothermal while oil, natural gas which are fossil fuels have the lowest. This

generally implies that renewable sources of energy have significant job creation potential compared with fossil fuel sources.

19.5.3. Safety of energy sources for power generation

Different energy sources have varying degrees safety when used in power generation as demonstrated in figure 19.5 below.

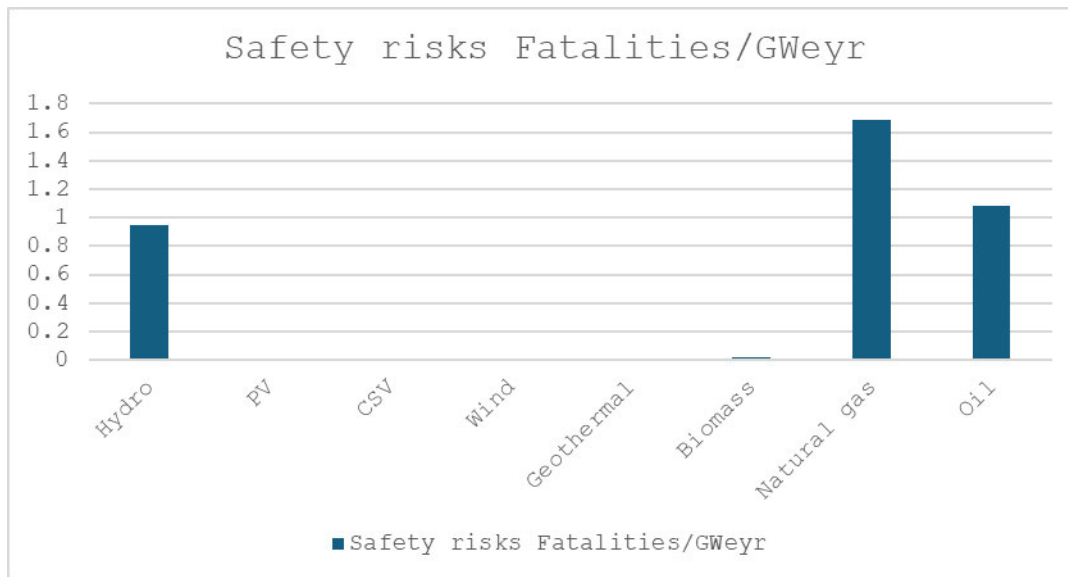


Figure 19.5: Safety risks for energy sources for power generation

From figure 19.5, it is noted that natural gas and oil which are fossil fuels have highest fatalities followed by hydro and biomass which is a renewable energy resources. Lowest fatalities are associated solar PV, CSP, wind and geothermal which indicate that renewable sources of energy are generally safer than fossil fuels sources.

19.6. Results and Discussion

In this section, the study identifies specific energy sources, their applications and role in the energy transition from a global perspective. These energy resources identify with their role are both renewable and no renewable energy sources. The same energy resource can be used in multiple conversion systems and power plants having different performance characteristics in terms of efficiency, environmental impact, and relative sustainability. Sustainable energy is a requirement because of the ever-growing demand for energy, environmental impacts, and significance of energy to socioeconomic development. Various measures put in place to realise sustainable energy transition include use of sustainable energy resources, employing advantageous energy carriers, efficiency improvement for energy systems, mitigating environmental impacts of energy systems, and peoples living

standards, change of lifestyle, improving energy affordability, acceptance improvement and promotion of equity.

19.7. Conclusions

Various energy sources are available for selection and use in heat and power generation. Whereas some energy resources have been in use for many years like coal, natural gas, oil, hydro and biomass, some resources are still under development and require massive investment in infrastructure and technology. They include hydrogen, biomethane, ocean thermal, ocean osmotic, wave and tidal energy. Most renewable energy resources like wind and solar are supplied freely by nature but require investment in infrastructure and technology which add to the final cost of energy.

CHAPTER 20:

PERFORMANCE ANALYSIS OF POWER PLANTS AND CONVERSION TECHNOLOGIES

20. Overview

In this chapter is a summary of work published in journal and conference referenced as [2, 22, 23, 29, 39, 186, 1047, 1048] on power plants and conversion systems and their sustainability indicators and relative ranking or competitiveness in delivery of sustainable electricity. Sustainability broadly refers to the ability to maintain or support a process continuously repeatedly. Sustainability seeks to avoid depletion of natural or physical resources so that they can continue being there for a long time. Sustainability is generally concerned with the protection of planet earth, mitigating climate change and promotion of the social development without endangering life and without leaving anyone behind. The concept of sustainability seeks to protect and serve the needs of both the present and future generations [2, 29].

20.1. Technical Sustainability of Power Plants

20.1.1. Energy Payback Ratio

Energy payback ratio is the ratio of energy produced during the power plants normal life span, divided by the energy required to pay for the construction, maintenance and fuel for the power generation facility [353]. A high energy ratio is an indicator of a good environment. Performance, while low payback ratio of 1 and 1.5, shows that the consumes nearly as much energy as it generates and should be avoided. A system with a low payback ratio, requires much more energy to maintain it and which generates more environmental impacts. The environmental impacts for fossil fuels are realized during extraction, transportation, and processing of fuels while for renewable sources, the main impact is from building or facility construction [326, 353]. The main benefit of using energy payback ratios as a metric is that is less affected by upstream choices of energy supply, which minimizes the fluctuation in evaluation of greenhouse gas emissions energy payback ratio one of the most reliable indicators of environmental performance. Energy payback ratio as an indicator minimizes fluctuations in results of studies without eliminating them. Renewable energies can have very large variations in energy payback ratios. due to wide variation of site-specific conditions i.e. topography for the case hydro, quality of the wind for wind energy, and solar intensity of

solar radiation for solar energy[206, 353]. Table 20-1 shows the payback ratios for different generation technologies.

Table 20-1: Energy payback ratio of different generation technologies. [22, 23, 39, 1049-1051]

	Technology/power plant	Range	Average	Rank
1	Natural gas fired Gas turbines -Open	2-4	3	22
2	Gas turbine -Combines cycle (Gas fired)	4-6	5	14
3	Geothermal wellhead	20-35	27.5	8
4	Geothermal conventional	30-40	35	7
5	Hydro pumped storage	0.5-1	0.75	27
6	Hydro river run off	170-267	218	2
7	Hydro with storage/reservoir	205-270	238	1
8	Wind -offshore	60-80	70	3
9	Wind -onshore	60-80	70	3
10	Bagasse power Plants	6-12	9	12
11	Coal power plants	3-8	5.5	13
12	Nuclear – Conventional	14- 16	15	10
13	Nuclear – Small Modular Reactors	10-20	15	10
14	Wave power plants	50-70	60	5
15	Tidal power plants	50-70	60	5
16	Diesel power plants	3-7	5	14
17	Fuel cells	1.5-3	2.25	23
18	Grid Scale Battery Storage	0.5-3	1.75	24

19	V2G	0.5-2	1.25	26
20	Solar PV	3-6	4.5	16
21	Solar CSP	3-8	4	18
22	Biomass (Energy crops)	2-5	3.5	19
23	Forestry biomass	3-6	4.5	16
24	Wate biomass	-	27	9
25	Biogas	2-4.2	3.1	21
26	Biomethane	1.5-2	1.75	24
27	Biodiesel	1.8-4.6	3.7	20

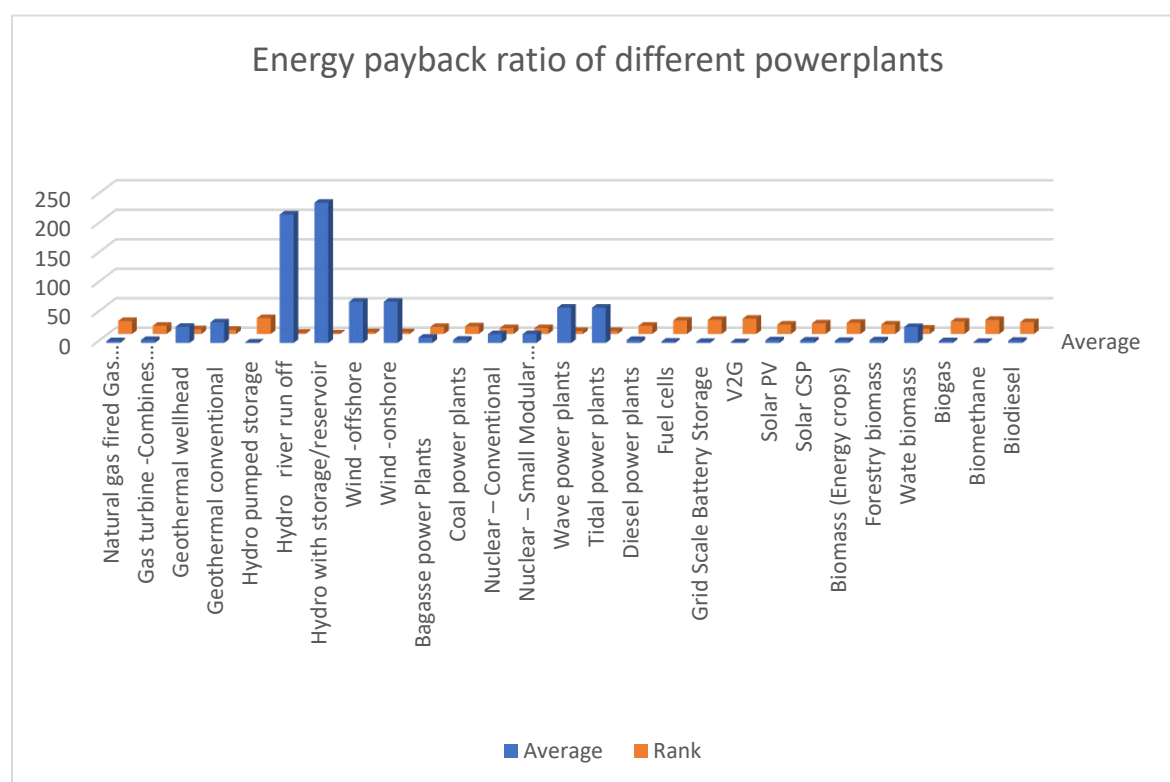


Figure 20-1: Energy payback ratios of different powerplants

From Table 20-1 and Figure 20-1, it is observed that hydro with reservoir has the highest payback ration, followed by wind. Coal, natural gas and cultivated biomass have the lowest

payback ratios. Among the emerging energy sources, hydrogen and biomethane have some of lowest payback ratios hence the need to invest in process efficiency improvements.

Fossil fuels sources of energy have low energy payback ratios compared to noncombustible renewables. Their payback ratios continue to over time due to reasons like depletion of reserves which tend to be replaced by wells that have higher energy requirement deep into the sea. Exploitation of fossil fuel resources like coal located far away from load centers and power stations increases transport costs by road and rail[1052].

Various analyses show hydropower clearly has the highest performance, with energy payback ratios of 205 and 267 while fossil fuels have of 5 to 7. The value for hydro with reservoir 205 and 267 for run-of-river. Best wind sites have payback ration of about 80 without back up. Biomass has about 7 for power from forestry waste and 5 for. planted trees due to higher energy inputs. The higher the distance of the power plants from biomass sources, the lower the payback ratio. Natural gas has a payback ratio of about 5 with some energy being spent on transportation over long distances. The ratio for natural gas power plants located close to the source of natural gas is higher. With high investment on transportation, the payback ratio for coal is also low at about 5 as well as investment on scrubbing of SO₂, which requires lime and other resources that need transportation and other investment in production and delivery on site and disposal[353].

Further investment in emission reduction technology like scrubbing of SO₂ can reduce the overall efficiency of coal generation and hence reduce payback ration while capture and sequestration of CO₂ will require huge investment in capital and energy for operation of scrubbing and disposal equipment while noting that sulfur is about 1% of coal and carbon is more than 50% of the coal. Therefore, mandatory investment in emission reduction technologies will reduce the overall efficiency and feasibility of coal and other fossil fuel power plants[322, 353].

20.1.2.Generation Efficiency /Conversion Efficiency [1053-1056]

Generation efficiency is used to express the efficiency of a generator or power plant as a percentage, by dividing the equivalent energy content of a kWh by the heat rate. Electricity is produced while some energy in the fuel ends up as waste heat or as electrical power. For a thermal system, the thermal efficiency of the electrical power generation is defined as this the electrical energy produced divided by the total energy released by the fuel consumed while waste heat of the power cycle goes released to the cooling water and the exhaust gases that

exit from which exit the power plant stacks. The cooling water heat is released in cooling towers as water vapor. [1057].

Table 20-2: Conversion efficiency of powerplants

	Technology/powerplant	Range	Average (%)
1	Gas turbines -Open	30-40	35
2	Gas turbine -Combines cycle	40-58	49
3	Geothermal wellhead	10-15	12.5
4	Geothermal conventional	10-17	13.5
5	Hydro pumped hydro	70-80	75
6	Hydro -small	70-90	80
7	Hydro – Large	90-95	92.5
8	Wind -offshore	24-54	38
9	Wind -onshore	24-60	42
10	Solar -photovoltaics	12-15	13.5
11	Solar thermal	14-23	18.5
12	Bagasse cogeneration power Plants	50-60	55
13	Biomass and biogas	30-40	35
14	Waste to electricity	22- 28%	25
15	Coal power plants	40-47	43.5
16	Nuclear – Conventional	33-45	34.5
17	Nuclear – Small Modular Reactors	33-37	35

18	Wave power plants	50-70	60
19	Tidal power plants	70-90	80
20	Ocean thermal	6-8	7
21	Diesel power plants (conventional)	20-40	30
22	Diesel power plants (with cogeneration)	40-80	60
23	Fuel cells	40-70	55
24	Grid Scale Battery Storage	65-91	78
25	V2G	60-90	70
26	Magnetohydrodynamic power plant	39.4-90	60

The generation efficiency of the various power plants is summarised in Figure 20-2 and Figure 20-3.

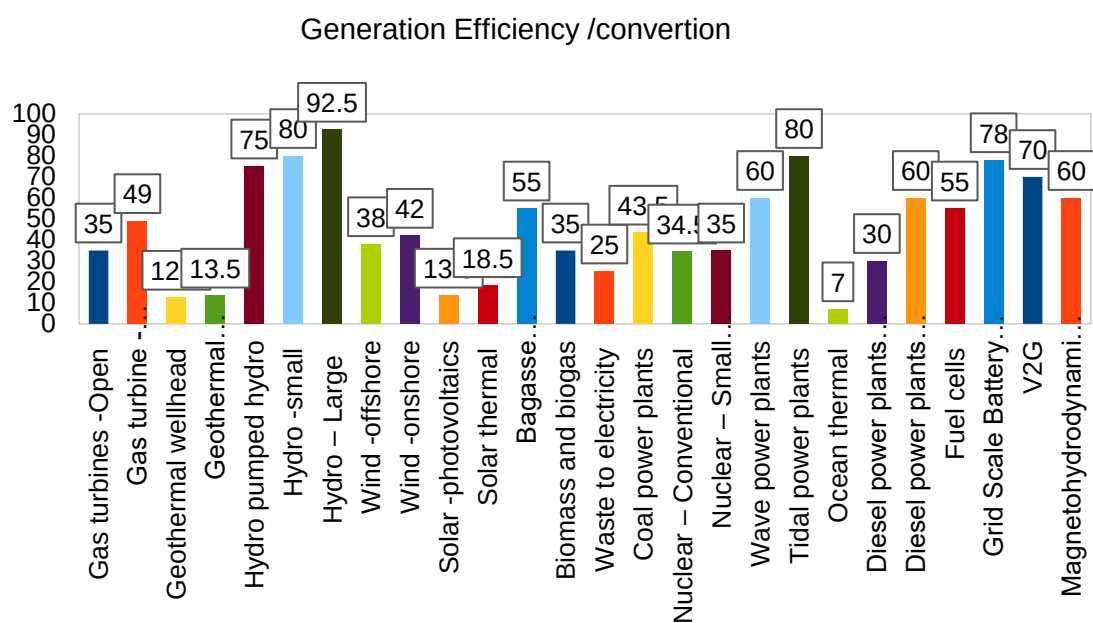


Figure 20-2: Bar graph of generation efficiency of various power plants

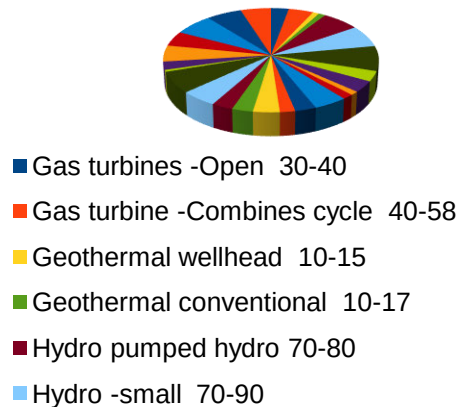


Figure 20-3: A pie chart of generation efficiency of different power plants

From Table 20-2, Figure 20-2 and Figure 20-3, it is noted that the large hydropower plants are the have the highest average generation efficiency on average basis.

This is an important parameter that is used to express the rate of conversion of the energy source to electricity. Generation efficiency influence the price of power and because high levels of waste is an indicator of inefficient and wasteful process which is unsustainable. Improving efficiency for inefficient processes working at 10% efficiency has potential to improve profits if 1% improvement made to efficiency. However, processes, that have already achieved 50% efficiency, need 5% improvement to attain similar gains in profits as those operating at 10%. This is because efficiency improvement has diminishing returns in efficiency improvements. [1058].

The range of energy conversion to electricity varies by resource with hydropower having the highest efficiency of all renewable electricity generating technologies currently available. Hydro is followed by wind then followed photovoltaics while geothermal power has the lowest efficiency among the technologies under consideration. Solar conversion efficiency varies greatly because of a large range of cell types available in the market but the ideal efficiency is 30% [59]. The highest solar efficiency is in crystalline silicon cells (including multi- and poly-crystalline) while the amorphous silicon has the lowest conversion efficiency. The efficiency of wind conversion also varies widely because of wide variation in quality of wind resources from one place to another. However, with proper site selection and good wind energy more than 40% efficiency can be achieved. The efficiency of geothermal energy conversion is the lowest due to low geothermal resource temperature.

20.1.3.Capacity Factor

Capacity factor is the ratio of maximum demand to capacity of a power station or power system. It is a measure of the utilisation of existing capacity for power generation. Power plants with high-capacity factors are ideal for base load applications and are generally more efficient.

Table 20-3: Capacity factors or various technologies[1059-1061]

	Technology	Minimum (%)	Maximum (%)	Average (%)
1	Coal	50	80	65
2	Gas power plants	50	60	55
3	Nuclear-conventional	90	95	92.5
4	Nuclear- SMR	80	90	85
5	Geothermal-conventional	90	98	94
6	Geothermal- Wellheads	70	90	80
7	Solar thermal	14	52	33
8	Solar-Photovoltaic	10	25	17.5
9	Wind onshore	21	52	36.5
10	Wind -offshore	21	60	40
11	Large Hydro	80	95	87.5
12	Mini/Micro Hydro	23	95	57.8
13	Biomass	51	80	65.5
14	Fuel cells	70	99	84.5
15	Magnetohydrodynamic generation	70	90	80

16	Diesel power plants	70	95	82.5
17	Bagasse power plants	60	90	75

The capacity factors for various power plants presented in Table 20-3 are also presented in Figure 20-4.

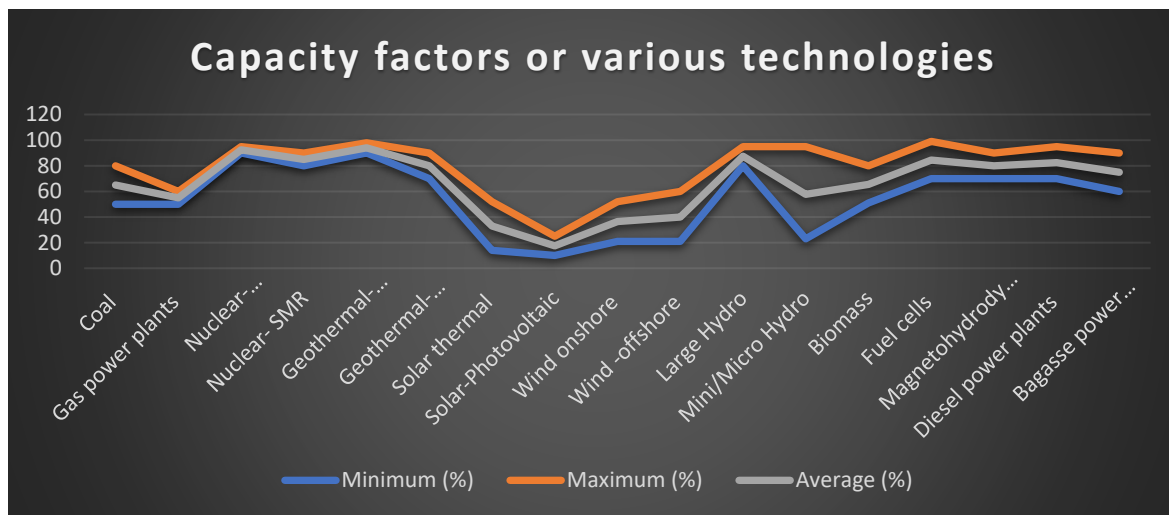


Figure 20-4: Capacity factors of various power plants

From Figure 20-4 and Table 20-3, it is noted that power plants with high-capacity factors include geothermal, hydro, fuel cells, nuclear and coal making them ideal for base load. Diesel power plants also with high-capacity factors are not ideal for base load power application due to high cost of fuel and emissions making them expensive and unattractive.

The Capacity factor (CF) of a power plant refers to the ratio of actual power generation to maximum possible output based on nameplate capacity of the power plant. The capacity factor is affected by factors like power condition, plant maintenance, plant availability, fuel price and quality and power plant design to electricity demand load profile i.e. whether as baseload plant, load-follower, or peaker. The capacity factor of variable renewables is affected by location, solar irradiation, and prevailing wind speed. Power curtailment is another factor which affects capacity factor as it is applied to assist in power system ability to integrate variable renewables. Fossil fuel power plants can be forced to reduce availability for more renewables, to be absorbed[1060]. The capacity factor refers to the percentage of power generation realised from the installed capacity and is usually stated on annual basis. Efficiency on the other hand measures percentage of energy input energy transformed to

usable or output energy. Capacity factor of the same power plant may vary from site to site for variable renewables e.g. the average for photovoltaics (“PV”) in Germany is between ~10–11%, but California, average annual capacity factor CF of 25% is achieved which implies that California yields about 2,5x the output identical PV plant in Germany [1062].

It is possible to adjust each technology’s average capacity factor (averaged over the course of its lifetime) e.g. historical operations of conversion technologies, coal, NGCC, and nuclear power plants have default capacity factors is 75% 60% and 85%, respectively, but users can individual influence the capacity factors to meet their generation needs or prevailing load profile.[1059].

20.1.4.Economic Life of the Power Plants

Economic growth is also driven by sustainability to produce equitable wealth for all without destroying the environment. Important factors include equal distribution of economic resources, or equitable access and benefits[2, 3]. Economic sustainability seeks to increase of regional per capita income, improve living standards of local people, reduce dependence on energy and enhance diversity of energy supply[1063].

Table 20-4: Economic life of power plants

	Technology/powerplant	Range	Average	Rank
1	Gas turbines -Open	20-30	25	11
2	Gas turbine -Combines cycle	30-40	35	5
3	Geothermal wellhead	1-20	10	20
4	Geothermal conventional	30-40	35	5
5	Hydro	40-100	70	1
6	Wind -offshore	20-25	22.3	16
7	Wind -onshore	20-25	22.5	15
8	Bagasse power Plants	20-30	25	11
9	Coal power plants	30-40	35	5

10	Nuclear – Conventional	40-50	45	2
11	Nuclear – Small Modular Reactors	20-40	30	8
12	Wave power plants	30-50	40	2
13	Tidal power plants	30-50	40	2
14	Diesel power plants	20-30	25	11
15	Fuel cells	10-20	15	17
16	Grid Scale Battery Storage	10-20	15	17
17	V2G	10-20	15	17
18	Solar PV	30-35	32.5	9
19	Solar PV	30-35	32.5	9

From Table 20-4., it is noted that different conversion technologies vary in their average economic life. The economic life of various power plants is also presented in Figure 20-5.

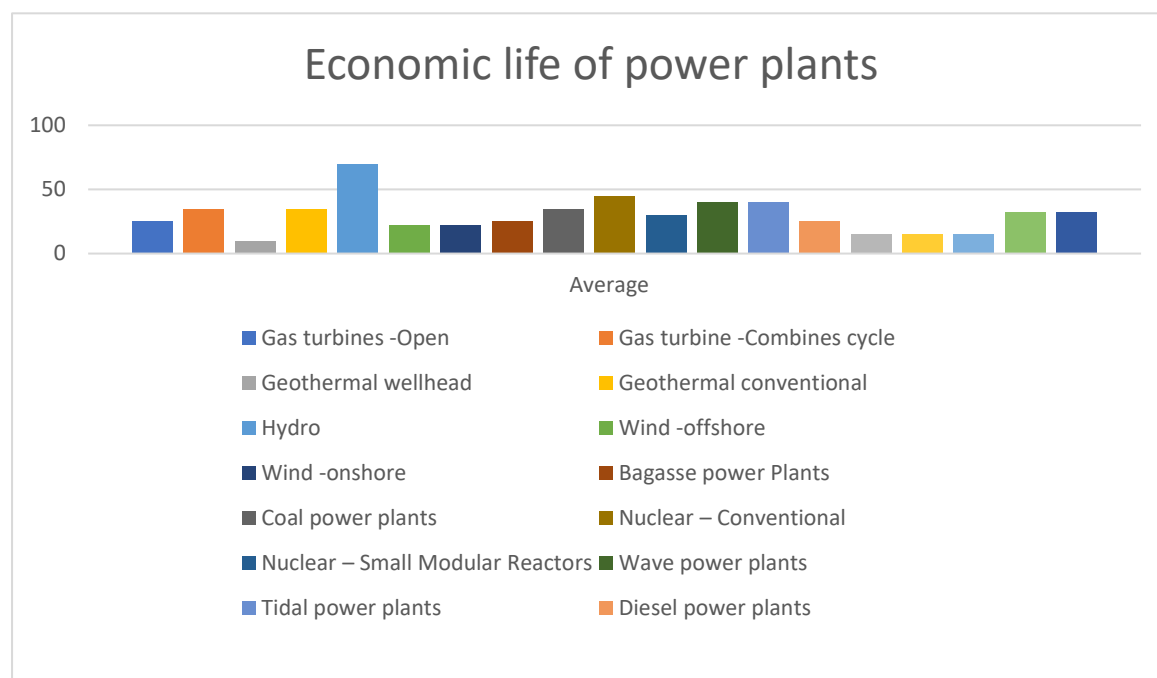


Figure 20-5: The economic life of various power plants

From Table 20-4 and Figure 20-5, it is noted that hydro power plants have the longest economic life followed by nuclear and geothermal. The V2G systems, grid storage and fuel cells have the shortest useful life. Power from power plants with longer life is generally cheaper since the capital costs are spread over a longer period, making them ideal for base load if operation and maintenance costs are lower.

20.2. Economic Indicators of Power Plant Sustainability

20.2.1. Levelized Cost of Power

The levelized cost of energy/electricity is a more accurate metric for comparing the power plants and cost of power generation. A more accurate measure of the total cost is the levelized cost of energy because it accounts for time over which the power plant is built and operated. Whereas the LCOE is spread across the entire life, hence a much smaller number, the overnight cost of capital is not spread over time at all.

Levelized cost can be taken as the lifetime expenses versus total expected generation, expressed in terms of the present value equivalent. Values necessary to calculate levelized cost of energy include:

- i. Annual investment expenditures
- ii. Annual operation and maintenance costs
- iii. Fuel expenditure in each year
- iv. Electricity generated in each year.
- v. The discount rate to be applied to future year's expenditures and plant output.

It is, therefore, an attempt to capture the full lifetime costs of an electricity generating installation, and allocate these costs over the lifetime electrical output, with both future costs and outputs discounted to present values.

20.2.2. Global Trend in Levelized Cost of Energy/Electricity

In Britain, gas is the largest source of electricity at 40% as of 2022 with varying cost of power. As a measure to reduce the share of high carbon sources, the government annually auctions contracts for new power plants with low carbon emissions particularly the offshore wind[1064]. Before year 2022 generators always received subsidies for electricity supply but the reverse is currently happening as they are paying the state instead, simply because renewables are now self-sustaining[1065]. For France which heavily relies on nuclear power, the Fukushima Daiichi nuclear disaster has forced introduction of new safety

investments to upgrade the French nuclear plants by about €4/MWh. For large scale solar power of capacity 50–100 GWh/year, the estimate of €293/MWh is provided while small household plants generating 3 MWh/year, cost between 400 and €700/MWh, based on the location. In France, solar remains the most expensive renewable source of electricity but the technology has become competitive due to higher efficiency and longer lifespan of photovoltaic panels and reduced cost of production since 2011 to reach the cost of less than €50/MWh. A study by the investment bank Lazard compared renewable and conventional sources of energy, assuming 60% debt at 8% interest rate and 40% equity at 12% cost" for its LCOE calculation. [79]

The average global Levelized cost of power from different sources is shown in Table 20-5.

Table 20-5: Global Levelized cost of generation by source in USD/MWh[1066]

	Technology	IPCC (2014)	IRENA (2020)	LAZARD (2020)	NEA (2020)	BANF 2021	IEA	Ave USD/MWh
1	PV (utility scale with fixed axis)	110	68	30	56	39	87.06	74.03
2	PV (Utility scale with tracking)			40		47		44
3	PV (residential)	150	164	189	126	-		157
4	Solar thermal	150	182	141	121		73	133
5	Wind (onshore)	59	53	40	50	41		49
6	Wind (offshore)	120	115	86	88	79		98
7	Nuclear -	65	-	97	50	-	30-	47

	conventional						35	
8	Hydro	-	22	47	-	68		46
9	Geothermal	60	73	80	99	-	104	69
10	Coal (CC)	61		112	99	-		91
11	Gas turbines	71	-	117	71	70	80	83
12	Fuel cells						\$79- 160	119.5
13	Small modular reactors (SMRs)						\$67	67
14	Fuel cells						200	200
15	Grid scale storage					50	50	50
16	Diesel power plants					65.43	65.43	65.43
18	Biomass power plants					53- 182	117.5	118
19	Bagasse						7-9	8

From Table 20-5, it is noted that there is significant variation in the global average. The data is also presented in Figure 20-6.

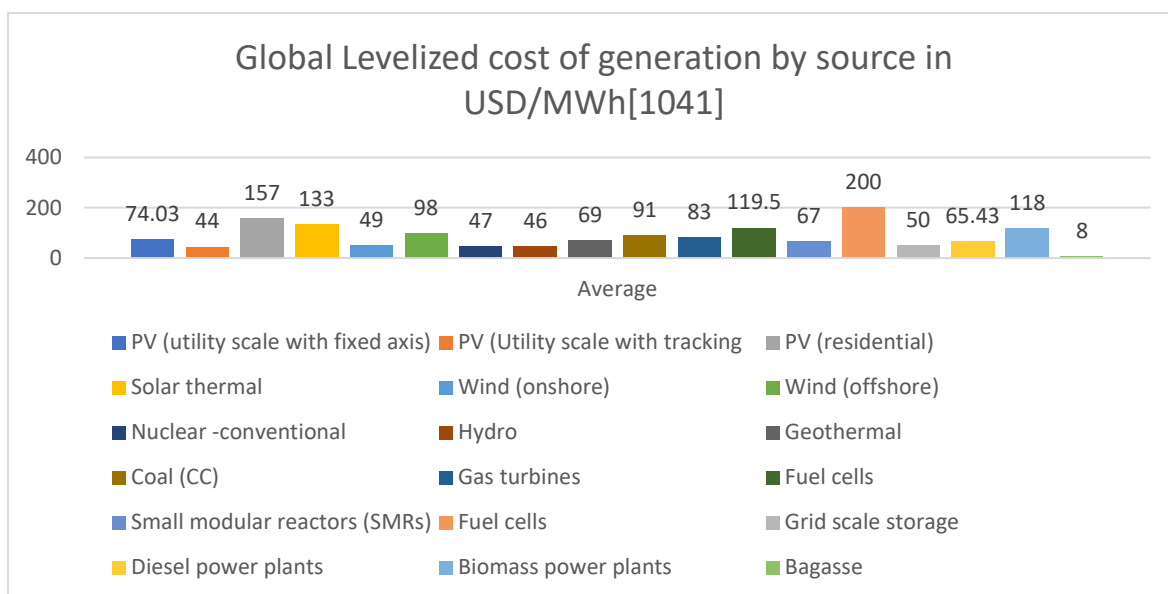


Figure 20-6: Levelized cost of power from different sources by different data sources.

From Table 20-5 and Figure 20-6, it is noted that electricity from bagasse cogeneration has the lowest levelized cost of power followed by PV (Utility scale with tracking) although data is limited. This is followed by hydro power and onshore wind is the cheapest. PV (residential) followed by onshore wind generation have the highest global average levelized cost of energy.

20.2.3. Electricity Price

Each energy resource and technology selected for electricity generation varies in price. Based on full life cycle average cost, the price ranges are as shown in table 19.6. The full life cycle cost of each energy generation technology considers the plant construction, plant installation, commissioning, facility operation, plant maintenance, cost of plant decommissioning, cost of recycling, and disposal cost of the plant or facility[1045].

Table 20-6: Unit cost of electricity by source[1045]

	Technology/Resource	USD/kWh	Average
1	Solar	0.240	0.240
2	Onshore Wind	0.05-0.06	0.55
3	Hydro	0.051	0.051

4	Geothermal	0.068	0.068
5	Coal	0.048	0.048
6	Nuclear	0.043	0.043
7	Nuclear -SMR	0.0373	0.0373
8	Gas	0.048	0.048
9	Biomass	0.070-0.13	0.10
10	Bagasse power	0.06-0.10	0.8
11	Diesel power plants	0.8-5	2.9

The unit costs or prices of power from different sources in Table 20-6 are also presented in Figure 20-7.

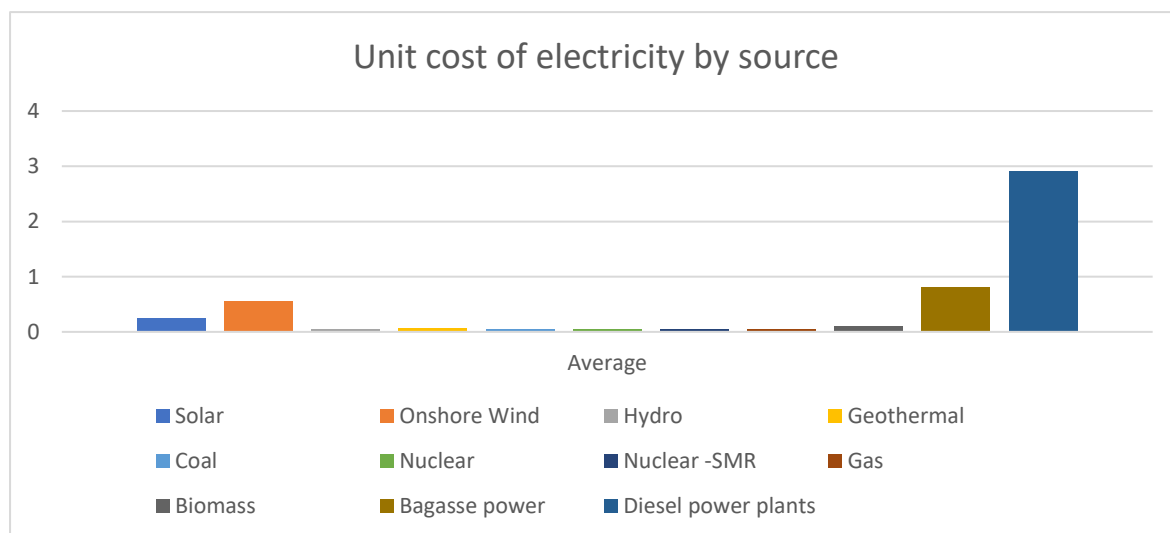


Figure 20-7: Unit cost of electricity from different sources of electricity

From Table 20-6 and Figure 20-7, it is noted that nuclear-SMR and bagasse power has the lowest price followed by hydro, geothermal and wind. Solar is the most expensive among the 4 main renewable sources of energy compared. Technological improvement has however ensured that solar is cheaper than coal and gas which are fossil fuels. The table shows that non-renewable sources are the cheapest per unit power lead by nuclear, followed coal and gas

while the renewables are more expensive. The average cost of photovoltaics is quite prohibitive under normal circumstances, at 24c/kWh[1058].

As a result of zero fuel consumption, non-combustion renewable energy sources and technology have high capital intensity but low running cost. The most significant cost in photovoltaics is purification of silicon, which consumes 60% of the production energy for frameless multi-crystalline module. Generally, capital costs account for about 95% of the life cycle costs for photovoltaics. As a result of this, variation in interest rate have significant impact on life cycle analysis [1045]. Through careful selection of generator sizes and type based on based on site specific characteristics can help minimize cost of wind projects. For hydropower, the construction of dams' accounts for nearly all hydro costs while operation and maintenance are usually low. Long gestation periods for geothermal energy projects increase project costs. Additionally, high costs and risks are associated with drilling, with drilling accounting for up to 50% of the total project cost.

All technologies exhibit wide-ranging values for price of power per kW h with photovoltaics having widest variation. Hydropower has the lowest average price of unit power with the average price being closer to the lowest unit price of electricity from hydro. Geothermal exhibits a lower range in price compared to wind even though average price is close to each other. Solar photovoltaics is the most expensive technology in terms of unit price of power [1045]

20.2.3.1. Capital Costs of Power Plants

Different methods are applied to compare the cost of building or developing power plants. In quick scan or quick comparison of power plants, firms often use look at the cost of building a power plant overnight, also called the overnight cost of capital. This is a hypothetical scenario since a power plant cannot be constructed in one night, however it evaluates the cost of building a power plant right away, with current prices. This provides a simple and quick reference for a power plant cost without due regard of the actual time taken and price fluctuation over time. The computation of overnight costs does not consider the interest rate which would account for the increase in the cost over time. The overnight cost is therefore on of the simplest costs of comparing the cost of different power plants.

Overnight cost of a power includes the following cost items/elements.

i.) Construction costs

These are costs related to the installation of utilities for the power plant, materials like structural steel , site like planning etc.

ii.) Mechanical equipment supplies and installation.

These are costs related to critical machines and equipment like generators, engines, boilers, cooling towers, steam turbines, condensers, photovoltaic modules, generators etc.

iii.) Electrical controls costs

These are costs related to the procurement and installation of equipment used to transform and transmit electric power produced e.g. transformers switchyards, distributed control systems etc.

iv.) Project costs

Project costs are incurred while the plant is being designed and constructed, I form of engineering costs, labor, scaffolding costs, construction management etc.

The real and estimated costs of power plants tend to vary significantly Real-life costs can diverge significantly from those estimates. Capacity factors can also be used to compare power plants and can be as low as 10-20% for some wind and solar applications, up to 50% range for offshore wind and as high as 90% for the most reliable nuclear and geothermal power plants[78, 109]. The average capacity factor of all commercial nuclear power plants in the world in 2020 was 80.3% which is less than the 83.1% for 2019. This value however includes outdated Generation II nuclear power plants Although peaking power plants have low capacity factors, they compensate by charging highest possible price when they supply power[364].

The generation capacity capital costs are expressed often as overnight cost per watt. Estimated costs are[1067]:

Table 20-7: Capital Costs of Conversion Technologies [1067-1069]

	Power plant technology	Energy source	Cost (USD/kW)
1	Combined cycle power plant	Gas/oil	1,000
2	Combustion turbine	Gas and oil	710
3	Onshore wind	Wind	1600

4	Offshore wind	Wind	6500
5	Solar PV (Fixed)	Solar	830-1800
6	Solar PV (tracking)	Solar	860-2000
7	Battery storage power	VRE	1380
8	Hydropower (conventional)	Hydraulic energy	2752
9	Geothermal	Thermal	2800
10	Coal (with SO ₂ and NO _x controls)	Thermal	3500-3800
11	Advanced nuclear	Atomic energy	6000
12	Fuel cells	Hydrogen, methane, etc.	7200

The data is also presented diagrammatically as Figure 20-8.

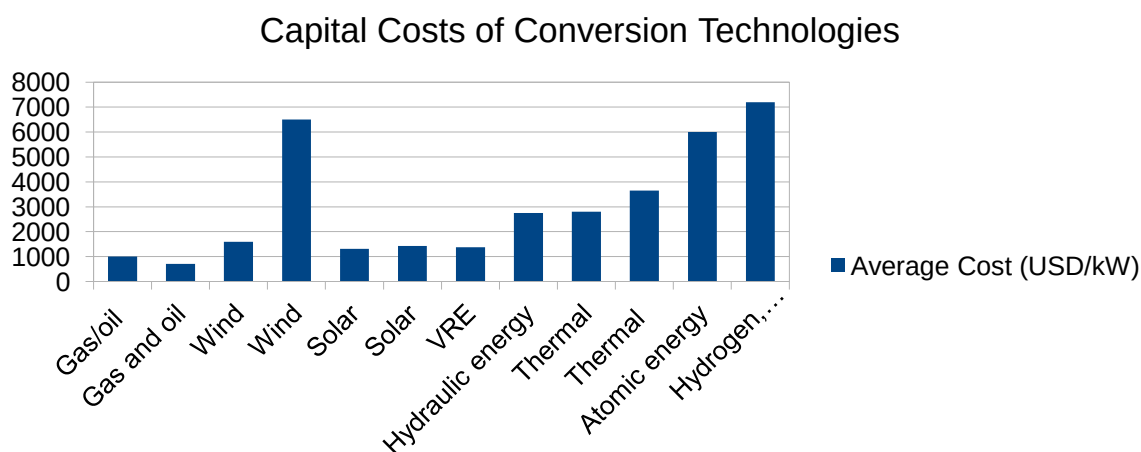


Figure 20-8: Capital costs of various conversion technologies

From Table 20-7 and Figure 20-8, it is noted that costs vary wildly for different power plants from place to place or time to time and whether interest is included in total cost. Capacity factors and the intermittency also impact or influence computation of costs. Power plant lifespan of various power plants also varies with oldest hydropower plants currently with over a century of existence while some nuclear power plants have existed for five or six

decades of continuous operation. Wind turbines have exhibited lower lifespan with some being less than 25 years before being retired. Solar panels also exhibit some an aging, which reduces the lifespan[1070].

20.2.4. Cost and Performance Characteristic of New Technologies

The various conversion technologies demonstrate variability in cost, with respect to the project size, power plant's location, and access to energy infrastructure like grid interconnections, supply of fuel, and transport. shows the weighted average cost for both wind and solar PV, based on regional cost factors for the specific technologies [357, 1067].

Table 20-8: Cost and performance characteristics of new central station electricity generating technologies[1067]

		First year	Size (MW)	Lead Time	Base O.N. costs \$/kW	Opt. factor	Total O.N. Cost (\$)/kW
1	Ultra-supercritical coal (USC)	2025	650	4	4074	1.0	4074
2	USC with 30% carbon capture and sequestration (CCS)	2025	650	4	5045	1.01	5096
3	USC with 90% CCS	2025	650	4	6495	1.02	6625
4	Combined-cycle—single-shaft	2024	418	3	1201	1	1201
5	Combined-cycle—multi-shaft	2024	1083	3	1062	1	1062
6	Combined cycle with 90% CCS	2024	377	3	2736	1.04	2845
7	Internal combustion engine	2023	21	2	2018	1.0	2018
8	Combustion turbine— aeroderivative	2023	105	2	1294	1.0	1294
9	Combustion turbine—industrial frame	2023	237	2	785	1.0	785

10	Fuel cells	2024	10	3	6639	1.09	7224
11	Nuclear—light water reactor	2027	2156	6	6695	1.05	7030
12	Nuclear—small modular reactor	2028	600	6	6861	1.10	7547
13	Distributed generation—base	2024	2	3	1731	1.00	1731
14	Distributed generation—peak	2023	1	2	2079	1.00	2079
15	Battery storage	2023	50	1	1316	1.00	1316
16	Biomass	2025	50	4	4524	1.00	4524
17	Geothermal	2025	50	4	3076	1.00	3076
18	Conventional hydropower	2025	100	4	3083	1.00	3083
19	Wind	2024	200	3	1718	1.00	1718
20	Wind offshore	2025	400	4	4833	1.25	6041
21	Solar thermal	2024	115	3	7895	1.00	7895
22	Solar photovoltaic (PV) with tracking	2023	150	2	1327	1.00	1327
23	Solar PV with storage	2023	150	2	1748	1.00	1748

Table 20-8 shows the various power technologies and the costs. Which is also presented in Figure 20-9.

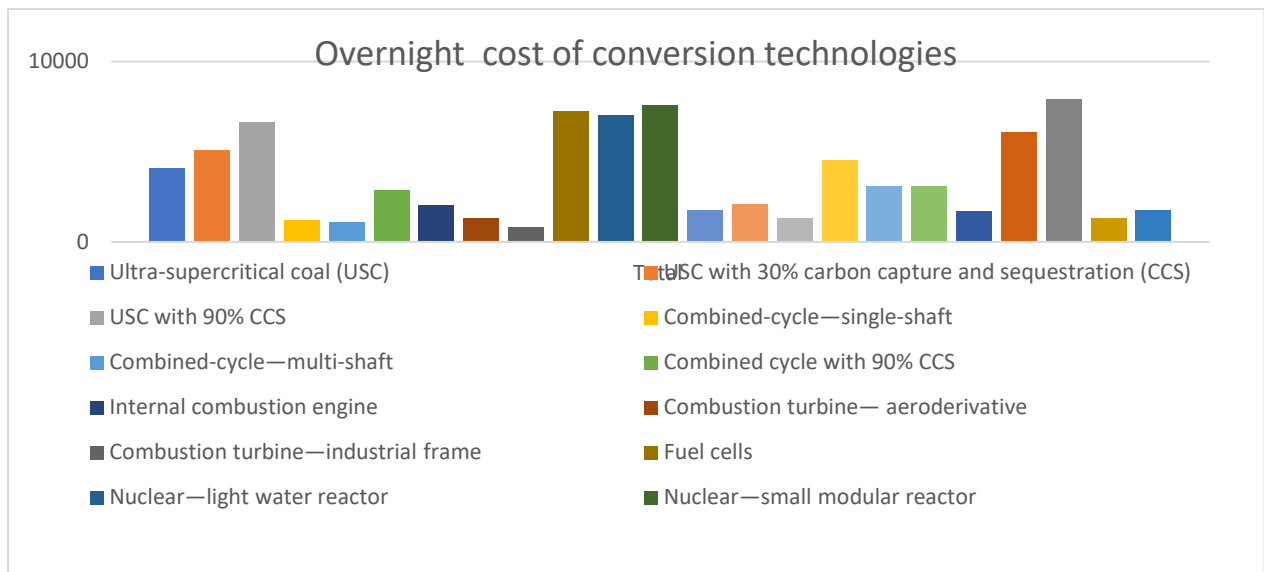


Figure 20-9: Overnight cost (O.N) cost of conversion technologies

Figure 20-9 shows the overnight cost of conversion technologies. The costs are for a typical facility for the generating technology before adjustment is made for regional cost factors.

Overnight costs do not include the interest accrued during power plant construction and development. Technologies having little commercial experience are allowed a technological optimism factor to capture the tendency to underestimate the full engineering and development costs incurred by new technologies in the process of research and development[373].

The apparent trade-off between capital and operating cost of power plants ensures that a comparison of overall costs of different power plant technologies is not a straightforward affair. It is for this reason that the use of the Levelized Cost of Energy" (LCOE), is a preferred metric in comparing lifetime costs of power generation.

The main elements of a power plants fixed costs are the capital costs and land. The capital costs of power plants vary from region to region mainly because variations in labour costs and regulatory costs like cost of getting permits and environmental approvals. Building power plants is time consuming venture and may vary from state e.g. building a power plant in the state of Texas may take as short as two years, but in the state of California, is much more difficult due to higher regulatory costs, the time-to-build take even more than ten [1071]. The average capital and operations cost of different power plants excluding subsidies, incentives, or social cost are shown in Figure 20-9.

Table 20-9: Typical capital and operating costs for power plants.

Technology	Capital Cost (\$/kW)	Operating Cost (\$/kWh)
Coal-fired combustion turbine	500 — 1,000	0.02 — 0.04
Natural gas combustion turbine	400 — 800	0.04 — 0.10
Coal gasification combined cycle (IGCC)	1,000 — 1,500	0.04 — 0.08
Natural gas combined cycle (NGCC)	600 — 1,200	0.04 — 0.10
Wind turbine	1,200 — 5,000	Less than 0.01
Nuclear power plans	1,200 — 5,000	0.02 — 0.05
PV Solar	4,500 and up	Below 0.01
Hydroelectric power plants	1,200 — 5,000	Below .01

From Table 20-9, it is noted that solar photovoltaic have the highest average capital cost followed by nuclear wind and hydroelectric power. Power plants with lowest capital costs include the natural gas combined cycle turbine, followed by coal fired turbines and coal integrated gasification combined cycle which are fossil fuel power plants. The power plants with lowest operating costs wind, photovoltaic and. hydroelectric power plants which are all renewable sources. The fossil fuel powered power plants have higher operating costs compared with the renewable sources. The main challenge with high capital costs is that they can significantly reduce the effectiveness of carbon prices[1072].

Regardless of the technology, power plants are defined by the following important features and characteristics influence the plant's operations:

i.) Ramp rate

The ramp rate defines how quickly a power plant can increase and reduce load in [MW/h] or in [% of capacity per unit time].

ii.) Ramp time

Ramp time refers to the time taken from the instant the plant is turned on to the moment it can start delivering power to the grid at the lower operating limit in hours [h]

iii.) Capacity

Capacity refers to the maximum output of a plant, in [MW]

iv.) Lower Operating Limit (LOL)

Lower operating limit refers to the minimum amount of power a plant can supply once switched on [MW]

v.) Minimum Run Time

This refers to the shortest time that a power plant can operate in [h] once switched on.

vi.) No-Load Cost

This refers to the cost of turning the plant on and keep it running or spinning in readiness to pick load or increase power output, in [\$/MWh]. It is also regarded cost of operation, i.e., the cost incurred by the generator which is independent of the amount of energy produced.

vii.) Start-up and Shut-down Costs

This refers to the cost of starting and stopping a powerplant plant in [\$/MWh]

Table 20-10: Ramp and run times for different power plants.

Technology	Ramp Time	Minimum Run Time
Simple-cycle combustion turbine	minutes to hours	minutes
Combined-cycle combustion turbine	hours	hours to days
Nuclear	days	weeks to months
Wind Turbine (includes offshore wind)	minutes	none

Hydroelectric (includes pumped storage)	minutes	none

From Table 20-10, it is noted that different power plants have different ramp time and minimum run times which affects their choice of application and cost of idle power. Nuclear power which has the longest tramp time and longest minimum run time makes it ideal for base load application, and less attractive for peak load applications. Although wind and hydro have the shortest ramp time and minimum run time, wind power plants being a non-dispatchable may not be ideal for just peak or base load application, instead may require further investment in storage for controllable use, which increases its cost.

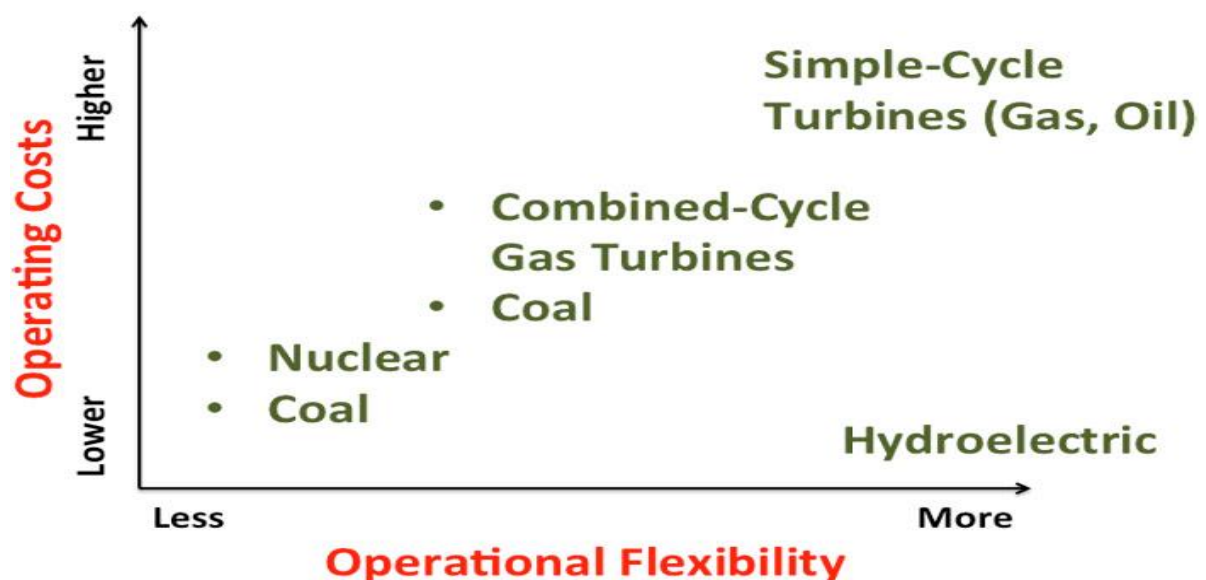


Figure 20-10: Relationship between operating cost and operational flexibility for different power plant technologies

Figure 20-10 shows that dispatchable power plants with high operating costs are the simple cycle and turbines followed by the combined cycle and coal power plants. These power plants are also characterised by high operational flexibility except hydro power plants which have the lowest operating costs but highly flexible in operations. Nuclear and some coal power plants ideal for baseload applications have significantly low operating costs but have the least operational flexibility.

The flexibility of power plants is determined by the minimum run time and ramp times of the generation source which vary greatly among power plants as a function of controls and

regulations, fuel type, and technology applied. Less flexible power plants having longer minimum run times and slower ramp times are ideal for base load power supply, while the more flexible power plants with shorter minimum run times and quicker ramp times are preferred for peak demand power supply. However, it is possible to run a nuclear power plant for like five hours and then shut it down, but this will cost more in form of wear and tear on the plant's components[1071].

The costs assigned to capital and operations activities are sensitive to assumptions made and inherent data inconsistencies. These assumptions and hence costs vary over time and with the power plant location and technology selected. Countries with less stringent may select the cheapest technology option, which may even involve used or second-hand equipment regardless of total emission or environmental impact. It is only by use of broad cost comparisons are possible to get a fair comparison of power plants because of wide variations in specific site costs and labour charges, exchange rates for currency, discount rates and power plant capacity factors. The rate of market liberalization also causes cost uncertainties in power generation due to the rate of market liberalization and acceptable level of intermittent renewable energy sources to the grid that do not cause reliability issues and expensive back-up requirements.

20.3. Environmental Sustainability Factors

Sustainability requires that nature and the environment are preserved through protection and rational use of resources. Environmental sustainability factors include conservation measures, commitment to use of renewable energy, water conservation and saving, incentivizing mobility, innovation in building and construction and sustainable architecture, which contribute to achievement of environmental sustainability[2, 3]. Environmental sustainability seeks to reduce global as well as local pollution and greenhouse gas emissions reduce natural resource exploitations and maintenance resilience i.e., ability adapt to changes, integrity, and stability of the ecosystem[1063].

20.3.1.Lifecycle Emissions

Detailed studies have shown that the average greenhouse gas emissions for renewable energy derived electricity production varies between 34 and 50 g CO₂-eq./kWh for wind and solar PV, respectively, 20–80 g CO₂-eq./kWh for concentrated solar power, and 40–80 g CO₂-eq./kWh for geothermal[1042].

Table 20-11: Life cycle emissions and ranking for various conversion technologies [1042, 1043]

	Energy	Conversion	gCO ₂ eq/kWh
1	Hard Coal	PC without CCS	1100
	Hard Coal	IGCC, without CCS	850
	Hard Coal	SC without CCS	950
	Hard Coal	PC with CCS	370
	Hard Coal	IGCC with CCS	280
	Hard Coal	SC, with CCS	330
2	Oil		840
3	Natural gas	NGCC, without CCS	430
	Natural gas	NGCC, with CCS	130
4	Hydro	660 MW	150
	Hydro	330 MW	11
5	Pumped hydro storage		7.4
6	Nuclear		5.1
7	CSP	Tower	22
	CSP	Trough	42
8	PV	poly-Si, ground-mounted	37
	PV	poly-Si, roof-mounted	37
	PV	CdTe, ground-mounted	12

	PV	CdTe, roof-mounted	15
	PV	CIGS, ground-mounted	11
	PV	CIGS, roof-mounted	14
9	Wind	Onshore	12
	Wind	Offshore, concrete foundation	14
	Wind	Offshore, steel foundation	13
10	Ocean energy	Ocean thermal, tidal and wave	8
11	Biomass energy		52
12	Lithium-ion storage		33
13	Hydrogen fuel		38
14	Bagasse		0.227
15	Diesel	Diesel power plants	1060

The data can also be presented diagrammatically in Figure 20-11.

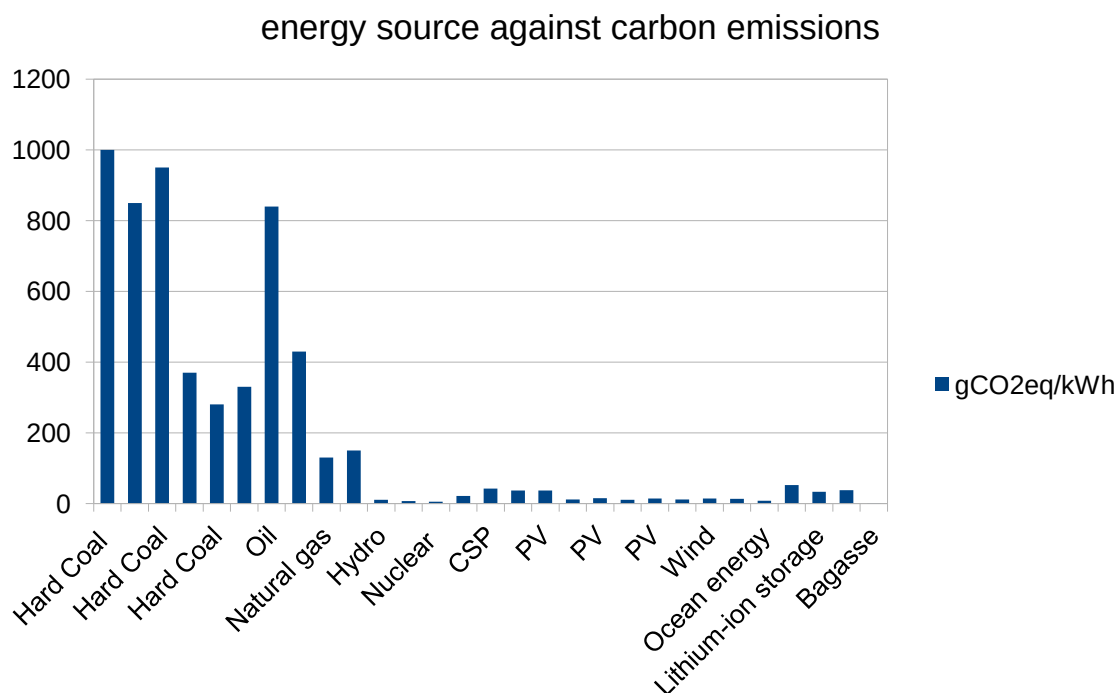


Figure 20-11: The emissions from various power plants using different energy sources.

From Table 20-11 and Figure 20-11, it is shown that the pulverized coal (PC) without CCS has the highest life cycle emissions followed by SC without CCS. The technologies and energy sources with lowest life cycle emissions based on the analysis is nuclear followed by pumped hydro storage and ocean energy. Bagasse power plants have the lowest carbon dioxide emissions hence most sustainable on basis of CO₂ emissions with coal being the least sustainable.

20.3.2.Land Use Requirements

Land is an important factor in sustainable energy development it is associated with other competing applications and land-use conflicts which may constrain the unprecedented rates of renewable energy deployment. Sites with potential land use conflicts require substantial development to achieve clean electricity goals [1073].

For solar energy, panels can be roof-mounted, which provides a negligible footprint during use while wind can be incorporated into agricultural hence reducing its share of the footprint. According to ref. [353] the total footprint for wind energy is 72 km² /TWh without allocating any share of this to agriculture while, [1074] noted that photovoltaic land requirement is 28–64 km²/TWh without dual-purpose allocation of land use. Hydro power has land requirement that is a function of local topography but it varies between 73 and 750 km² /TWh per year [1075]. According to [1076] the land requirements for hydro is as low

73 km² /TWh. Of the renewable sources under consideration, geothermal power plants have the small surface footprints, and has major power plant elements placed underground[1077]. The entire geothermal field is used for calculation of footprint due to the risk of land subsidence while typical land requirements for geothermal power is 18–74 km² /TWh.

Land used is approximated to account resource production, power plant land needs, land for transport and transmission, and waste storage space[1045, 1058]. The final assessment is summarised in Table 20-12 which shows the typical land requirements for solar, wind, hydro, and geothermal energy resources.

Table 20-12: land requirements [1041, 1078, 1079]

	Technology/powerplant	Average land (m ² /MWh)
1	Gas turbines -Open	50,181.064
2	Gas turbine -Combines cycle	50,181.064
3	Geothermal wellhead	4,350
4	Geothermal conventional	4,350
5	Hydro Run off river	1,275,570.272
6	Hydro, storage	1,275,570.272
7	Hydro pumped storage	1,275,570.272
8	Wind -offshore	285,708.316
9	Wind -onshore	285,708.316
10	Solar photovoltaics	176,038.41
11	Solar-thermal	176,038.41
12	Bagasse power Plants	1,100
13	Coal power plants	49,371.692
14	Nuclear – Conventional	51,395.122

15	Nuclear – Small Modular Reactors	51,395.122
16	Wave power plants	310
17	Tidal power plants	310
18	Ocean thermal	310
19	Ocean osmotic	310
20	Diesel power plants	900
21	Fuel cells	700
22	Grid Scale Battery Storage	34,398.31
23	V2G	34,398.31

The land requirements for different power plants presented in Table 20-12 is demonstrated in figure 20.12.

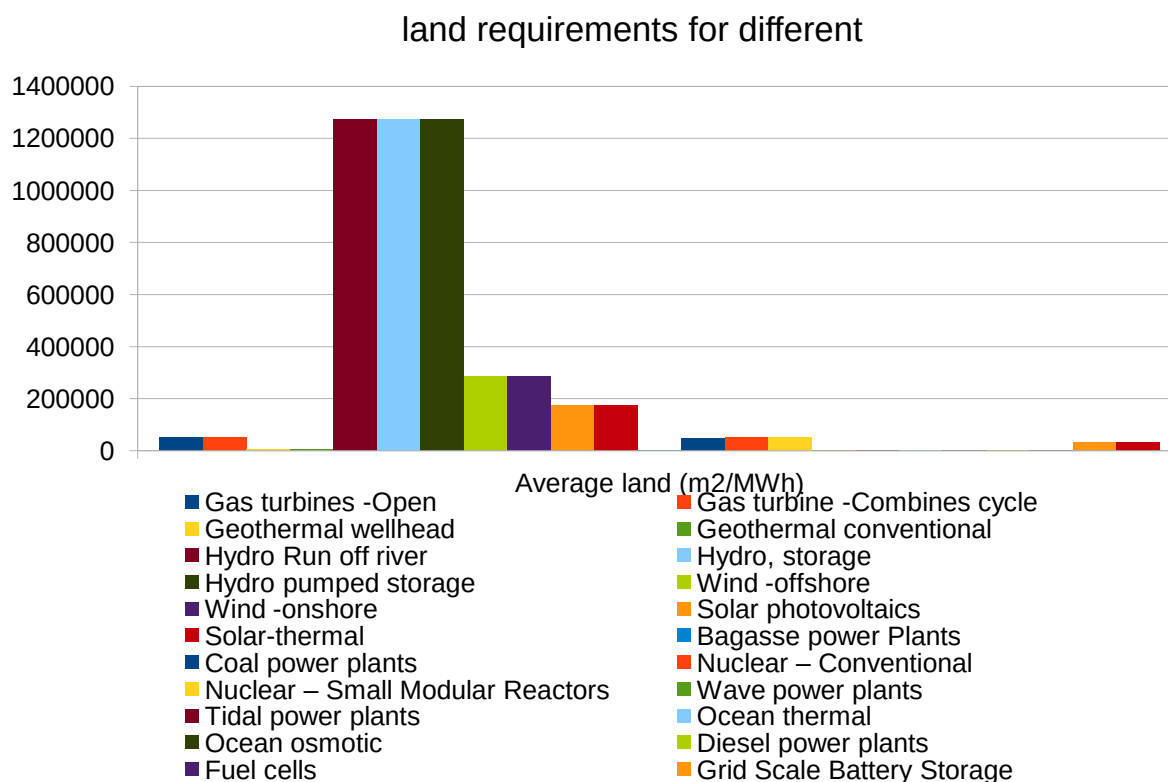


Figure 20-12: Land Requirements

From Table 20-12 and Figure 20-12, it is noted that hydro power plants have the highest land requirements followed by solar and wind power plants, while ocean power sources i.e. ocean thermal, osmotic, wave and tidal power plants have the lowest land requirements.

Land is an important factor in sustainable energy development it is associated with other competing applications and land-use conflicts which may constrain the unprecedented rates of renewable energy deployment. Sites with potential land use conflicts require substantial development to achieve clean electricity goals [1073].

Power generation is energy intensive, and each source has some environmental and ecological footprint. The various energy and power sources have different direct and indirect land requirements [1076]. The land is used at different stages for resource production, power plants, for transport and transmission, and waste materials[1075]..

20.3.3. Water Consumption

Power generation is a major driver of water stress globally and this is likely to be exacerbated because of growing demand and electricity generation. In certain scenarios, emission mitigation benefits introduce higher pressure on water resources e.g. many climate stabilization scenarios apply carbon capture and storage (BECCS) which is a very water-intensive as a negative-emission technology, option. It is important to incorporate water stress in energy system planning [1080]

Power systems withdraw and consume water to a degree depending on technology applied Water consumption is an accurate indicator of sustainability as it removes water from circulation with some environmental impact. Hydro dams lose a lot of water through evaporation, depending on dam size, volume per square meter and ambient temperatures[1081]. Water is needed for cooling and other operations [50]. Geothermal plants generate the highest amount of up to 300 kg/kWh[1081, 1082]. Solar and wind have very little life cycle consumption of water. It is used in operation and maintenance, and the production of photovoltaic modules and wind turbines. Wind power generation has the lowest water consumption among various technologies as shown in Table 20-13.

Table 20-13: Water consumption of power plants [1041]

Technology/powerplant	Water consumption range (kg/kWh_	Average (kg/kWh)

1	Gas turbines -Open	78	78
2	Gas turbine -Combined cycle	78-100	89
3	Geothermal wellhead	12–306	156
4	Geothermal conventional	12–306	156
5	Hydro Run off river	60-70	65
6	Hydro, storage	60–70	65
7	Hydro pumped storage	60–70	65
8	Wind -offshore	1	1
9	Wind -onshore	1	1
10	Solar photovoltaics	10	10
11	Solar-thermal	10	10
12	Bagasse power Plants	10-16	8
13	Coal power plants	78	78
14	Nuclear – Conventional	15–30	22.5
15	Nuclear – Small Modular Reactors	15–30	22.5
16	Wave power plants	65–70	67.8
17	Tidal power plants	65–70	67.8
18	Diesel power plants	1-2.5	1.75
19	Fuel cells	2	2
20	Grid Scale Battery Storage	1	1
21	V2G	1	1

Table 20-13 the varying water requirements for different power plants and energy conversion systems which is also presented graphically in Figure 20-13

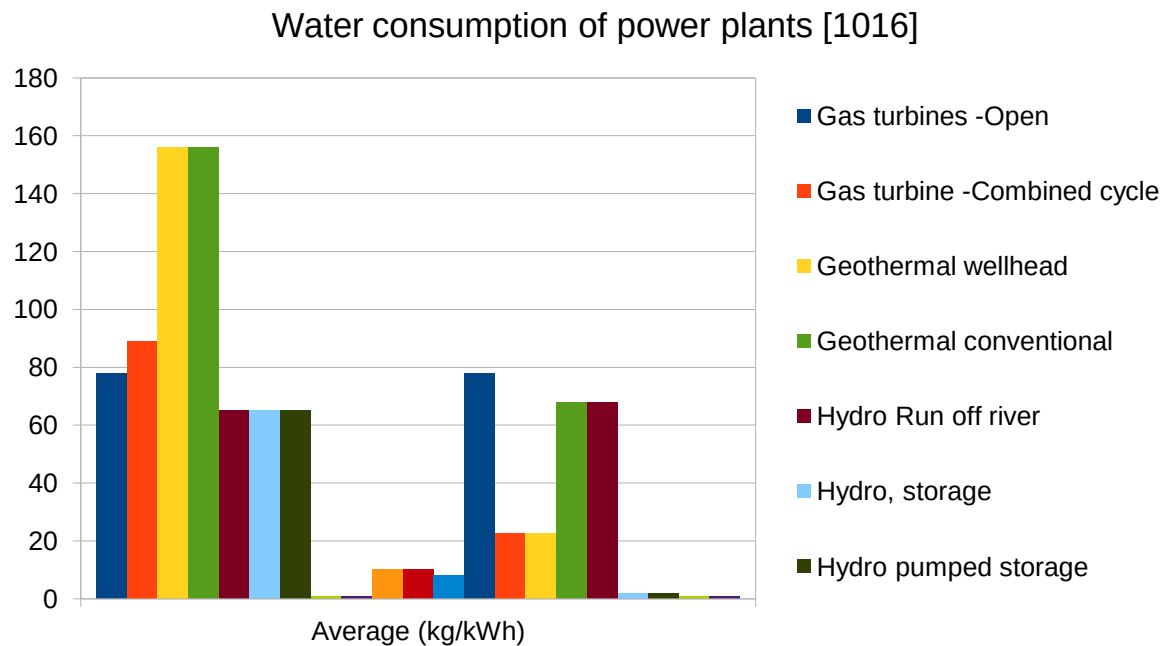


Figure 20-13: Water consumption by different power

From Table 20-13 and Figure 20-13, it is noted that wind has the lowest water consumption followed by solar. Geothermal has the highest water consumption ahead of coal and gas power generation.

20.4. Social Sustainability

Social sustainability of power plants and energy conversion systems seek to enhance social development, develop cohesion in society and cultures to attain satisfactory levels of quality of life, education, and healthcare. Another important aspect in social sustainability is gender equality[2, 3]. Social sustainability seeks to achieve global peace and harmony, social cohesion, stability, social participation, institutional development, and respect for cultural identity. Other important social objectives are reduction in unemployment and improvement in the quality of jobs, higher regional cooperation and cohesion, and poverty reduction[1063].

20.4.1. Job Creation

In this research, the total direct jobs are a sum of jobs created at various stages like equipment manufacturing, construction and installation, operations and maintenance, energy supply, decommissioning of power plants. The manufacture of equipment and components for a

power plant project takes months, years, weeks, or days hence these jobs represent relatively temporary employment compared to the to the entire plant lifetime and are therefore expressed as job-years, or the total number of full-time jobs needed. The jobs created per generation technology is presented in Table 20-14.

Table 20-14: Jobs created per energy source.

	Technology/powerplant	Jobs/MWh	Average
1	Gas turbines -Open	5-6	5.5
2	Gas turbine -Combines cycle	4-5	4.5
3	Geothermal wellhead	0.5-1	0.75
4	Geothermal conventional	0.8-0.98	0.89
5	Hydro -with storage	8-12	10
6	Hydro -River run off	5-8	6.5
7	Hydro -pumped hydro	3-4	3.5
8	Wind -offshore	11-14.2	12.6
9	Wind -onshore	9-14	11.5
10	Bagasse power Plants	5-10	7.5
11	Coal power plants	5-10	7.5
12	Nuclear – Conventional	0.5-0.1	0.75
13	Nuclear – Small Modular Reactors	1-2	1.5
14	Wave power plants	1-3	2
15	Tidal power plants	1-3	2
16	Diesel power plants	1-3	2
17	Fuel cells	3-5	2
18	Grid Scale Battery Storage	1-2	1.5

19	V2G	1-2	1.5
20	Solar PV	12-16	14
21	Solar CSP	7-10.56	8.8
22	Biomass and waste	6-18	7

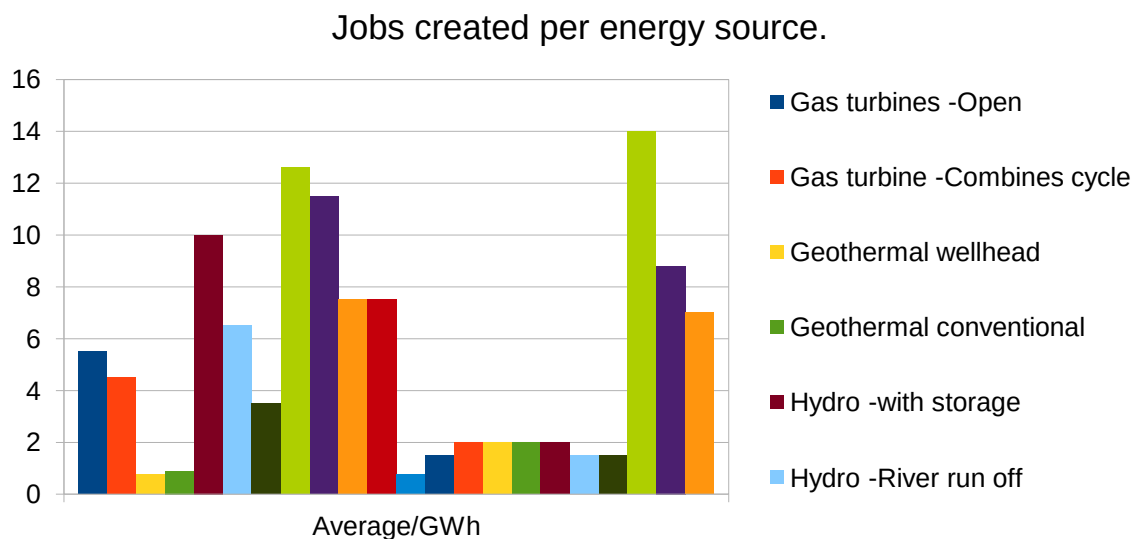


Figure 20-14: Jobs created per energy source.

From Table 20-14, it is noted that solar photovoltaic has the highest positive social impact in terms of job created per unit power capacity while geothermal and conventional nuclear have the lowest impact in terms of jobs created per unit power output.

Sustainable energy creates new wealth, jobs besides reducing negative impacts on the environment. Job creation is an important aspect to has policy ramifications globally and should therefore be explored in sustainability assessment. Studies show that global energy transition will have a positive impact on the future growth and stability of economies around the world.

20.4.2.Other Social Impacts

All sources of energy are associated with both negative and positive impacts. Most renewable sources of energy ae locally available making renewables to offer the opportunity for electricity generation and supply. Most countries of the world are not endowed with fossil fuel sources of energy and must be imported from other countries. [1045, 1083]. Impacts and

their relative magnitudes for the technologies under consideration are summarised in Table 20-15.

Table 20-15: Other social impacts of different energy sources and powerplants

	Energy resource	Impact	Magnitude
1	Solar	Toxins and visual effect	Minor-Major minor
2	Wind	Bird strike	Minor
		Noise	Minor
		Visual effect	minor
3	Hydro	Displacement	Minor-major
		Agricultural	Minor-major
		River damage	Minor-major
4	Geothermal	Seismic activity	Minor
		Oduor	Minor
		Pollution	Minor-major
		Noise	Minor
5	Nuclear	Radioactive radiations	High
		Land pollution	High
		Visual effect	Minor
6	Diesel	Noise	Medium
		Air pollution	High
		Visual effect	Low
		Land pollution	Low
7	Hydrogen fuel cells	Fire risk from hydrogen	High
		Heat pollution	major High
		Noise pollution	Low
8	Gas turbines	Noise	Medium
		Air pollution	High
9	Ocean thermal conversion	Ocean pollution	Medium
		Visual effect	Medium
		Interference with marine operations	Medium
10	Wave power plants	Ocean pollution	Medium
		Visual effect	Medium
		Interference with marine operations	Medium
11	Tidal power plants	Ocean pollution	Medium
		Visual effect	Medium
		Interference with marine operations	Medium
12	Magnetohydrodynamic power systems	Noise	Low
		Visual effect	Medium
13	Biomass power generation	Noise	Medium
		Air pollution	Medium
14	Coal	Air pollution	High
		Visual pollution	High
		Noise	High
		Land pollution	High
15	Natural gas	Air pollution	High
		Noise	Mild
		Fire risk	High
		Visual pollution	Low

From Table 20-15, it is shown that wind has the highest positive social impact, followed by solar power generation. Geothermal energy has the least social impact ahead of hydro power generation. Coal has the highest environmental impact in terms of land pollution air pollution and visual effect, followed by natural gas and diesel power generation.

20.5. Institutional Sustainability Assessment

Energy policy and regulation are critical to implementing renewable energy and the governance of natural resources. Institutions should prioritize the support to ensure reliable and sustainable energy transition. It therefore crucial to establish policies, legislation, and institutional structures to sustain renewable and sustainable energy[2, 3, 1084]. Table 20-16 summarises the level of institutional support for various power ants and energy systems towards the energy transition.

Table 20-16: Institutional sustainability assessment of power plants

	Technology/powerplant	Remarks/comments
1	Gas turbines -Open	Turbines have been in use for many years and therefore the industry is well regulated and standardised to enable wider adoption. Policy measures should be put in place to increase efficiency and use of cleaner fuels.
2	Gas turbine -Combines cycle	
3	Geothermal wellhead	Many countries are yet to embrace this technology through policy and legislation except few like Kenya
4	Geothermal conventional	With huge upfront cost and risks, state support is needed by separating resource identification and power plant development. Governments should protect investors from these risks by financing risky undertakings
5	Hydro river runoff	Many countries have put in place legal and institutional framework to guide exploitation of hydro energy resource
6	Hydro pumped hydro	
7	Hydro with storage	
8	Wind -offshore	Wind is a very important energy resource for the transition.

9	Wind -onshore	However not many countries have in place the legal, institutional and policy framework to encourage and guide wind energy and power generation e.g. guidelines on feed in tariffs, invest guidelines and institutionalised wind energy data including wind maps
10	Bagasse power Plants	Policy and institutional support needed to promote sugarcane bagasse. Only few countries including Mauritius, India and Brazil have institutionalised bagasse cogeneration as a source for power for the grid
11	Coal power plants	Legislation to support clean coal technologies needed. Many countries have a legal framework to guide the exploitation of coal power plants
12	Nuclear – Conventional	Nuclear energy exploitation is highly institutionalised with rules, regulations and policies being almost mandatory for countries developing and exploiting this energy resource. However, the small modular reactors (SMR) are still evolving as a technology and hence the institutional framework is also still developing
13	Nuclear – Small Modular Reactors	
14	Wave power plants	Still developing as the technology is not fully commercially established
15	Tidal power plants	Still developing as the technology is not fully commercially established
16	Ocean thermal powerplants ((OTEC)	Still developing as the technology is not fully commercially established
16	Diesel power plants	Diesel power plants have been used for many uses in emergency and peak power supply. However due to cost and environmental concerns, they are not generally acceptable in most developed countries. They remain important source of grid power in many developing

	countries
17 Fuel cells	Fuel cells are still developing with the technology nearing maturity. Sustainable development requires further development of standards, technology, regulations, and policy guidelines by authorities
18 Grid Scale Storage	Storage plays an important of load balancing for the grid which also increased the uptake of variable renewable like wind and solar. The main challenges to be addressed by policy makers, governments and authorities is to increase storage capacity, reduce costs and improve response time to address fluctuations
19 V2G	The V2G relies on the development of charging infrastructure, development of storage batteries that sustain a longer distance, cost reduction for electric cars and the development of the smart grid to manage millions of vehicles discharging and charging to the grid. Therefore legal, policy measures, standardization and development of the smart grid should be prioritized for successful V2G as a transition strategy

From Table 20-16, it is noted that. For conventional power plants like hydro, diesel power plants, coal and nuclear, many countries globally have a legal and regulatory framework to guide their deployment and operations. However, new but promising options like fuel cells, V2G, ocean energy sources require further technological development and an enabling policy, legal and regulatory environment which constitute the institutional dimension of energy sustainability.

The energy transition requires different economic, policy and regulatory changes to manage better the diverse processes involved. Regulation and standardization will lead to effective energy efficiency [1084]. It is effective policies and regulations that help in achieving the goals. Local regulations should encourage responsibility and compliance to accelerate the renewable energy transition.

20.6. Power Generation Modelling

Optimizing the future power generation mix can be done by using the Net Present Value (NPV) of the entire system examined as optimization criterion. It is necessary in this case to the future electricity prices to generate results. Optimization can also be done by focusing on minimizing the power generation cost whose advantage is that no assumption over the future electricity prices is needed; which eliminates a significant source of uncertainty. The benefit of focusing on minimum generation cost is that positive financial yields are maximized, regardless of the price of electricity price. It also implies minimization of the cost passed on to the final consumers[1085]. Possible commercial tools available for the approach are Wien Automatic System Planning Program (WASP-IV) and MARKAL.

MARKAL and WASP are optimization models, that apply linear programming techniques to determine the least cost solution to meet demand subject to some constraints. MARKAL is designed to analyze the overall energy system and analysis of various scenarios and issues like internalization of external costs of power generation applied to the electricity sector for analyzing, potential for CO₂ emissions reduction, and future demand projections. In a typical application of this approach medium-range planning economics of alternative fuel options in power generation can be done based Levelized generation cost methodology for comparison. Similar approach can be applied to determine the electricity generation cost, focusing mainly on establishing scale economies, overcapitalization, and technological progress for the past years as well as minimization of power generation cost [1085].

At the international scale, decision support tools have also been developed aimed at achieving global optimal solutions mainly taking into account financial and economic conditions and specific international level constraints. MARKAL model has been used to perform analysis for the world energy sector, divided into five extended regions. Other studies pointed out to the fact that if the estimates of damage costs from fossil fuel power plants are internalized into the price of the electricity, many renewable technologies particularly wind and biomass and solar could be financially competitive with coal plants [1085].

20.7. Results and Discussion

This chapter presents the available power generation technologies and their sustainability indicators. The various technologies are assessed for their sustainability and role in the energy transition. Sustainable energy technologies are needed to develop sustainable energy

for development. The transition to sustainable energy development requires changes that reduce t emissions, substitute fossil fuel-based power with low carbon and renewable energy (RE) and enhancement of energy efficiency. The world has realized significant growth in integration of renewable energy sources to reach double-digit percentages of electricity production, accounting for 29% of global electricity mix in 2020 compared to 18% in 2009., although fossil fuels still dominate the mix. However, the additions to capacity by renewable sources outperformed both fossil fuel and nuclear capacity combined capacity increase. The main reasons for this trends is concerns over global warming, climate change, cost reductions, and energy security [1086].

Energy has numerous environmental impacts which must be controlled to ensure it positively influences the living standards and economic development with minimum harm to the environment. Sustainable energy is associated with high efficiency, mitigate lifetime environmental impacts, and address nontechnical like better living standards and lifestyles, affordability, acceptance by society and guarantee equity[1087]. The challenge in energy planning is selecting an optimal option and mix among renewable resources [58].

Generation planning should consider the environmental and economic factors into account. Common input indexes include generation capacity, electricity cost/price generation cost, and land use while output indexes include total electricity generation, job creation and emissions[153]. Within the economic dimension of sustainability, feed in tariff, and cost of energy are important sub-criteria. Generally, investments are higher for renewable technologies than conventional sources, i.e. fossil fuels [1088]. On the environmental dimension of sustainability, CO₂ emissions reduction ability is generally more valued than impact on environment and land requirement sub-criteria.

In the ranking, where available values exist as a range, average values are applied. For quantifiable, values, average and range values were considered simultaneously, where significant overlap between values exist. Qualitative assessment was applied where quantitative values are not available like availability, limitations, and social impacts. On resource limitation, hydro was the least limited, with superior qualities to provide base load power, flexibility of operation and number of feasible locations globally. Hydro is followed by wind as the second best for availability, limitations, and social impacts. Geothermal is more unlimited globally, with less suitable locations for resource development. In this analysis, solar classified as the most limited mainly because storage capacity is still limiting and cannot store enough for nights and on cloudy times.

Wind is allocated the list social impacts when social impacts were considered, because of its benign nature. Solar has the least social impacts after wind owing to the technological progress careful management during manufacture and proper site selection mitigate its potential negative impacts. Geothermal energy comes after wind with the main social impact being incidences of seismicity and pollution potential from various gaseous emissions and brine effluent. These analysis places hydro the fourth after geothermal indicating higher negative social impact from hydro primarily because of many people and animals displaced during dam and reservoir development.

This study suggests that wind energy is the most sustainable renewable energy resource and technology followed by hydropower then solar energy. Geothermal energy is the list sustainable renewable energy resource among the four main non-combustible renewable sources of energy. was found to rank the lowest from the four non-combustion renewable energy sources and technologies. These ranking is based on the global parameters and may not be necessarily the same for specific countries or regions of the world. The significance of specific sustainability may change ranks based on site or location under consideration.

20.7.1.Power Plants and Applications

Power plants and energy conversion systems have different characteristics derived from the energy resource used and the plant design making them ideal for different applications on the grid power supply. The application of various power plants is summarised in Table 20-17.

Table 20-17:The various power plants and role in grid power supply

	Technology/powerplant	Energy Resources and prime mover	Characteristics Applications
1	Gas turbines -Open	Multiple combustion fuels e.g. natural gas, biogas, biomethane,	Power generation and aviation application. Ideal for peak power, mobile and emergency power
2	Gas turbine -Combines cycle	Combined cycle	Power generation, for peak and intermediate power
3	Geothermal wellhead	Wellhead power plants	Temporary and permanent power

			generation
4	Geothermal conventional	Dry and wet steam technologies	Power generation, ideal for base load power supply
5	Hydro Run off river	Run-off River	Base load, non-dispatchable
6	Hydro, storage	Storage	Base load, intermediate and peak supply
7	Hydro pumped storage	Hydro, for Peak, dispatchable	Energy storage system, peak, dispatchable
8	Wind -offshore	Wind energy, wind turbine generator	Power generation and pumping
9	Wind -onshore	Wind energy,	Power generation and mechanical application
10	Solar photovoltaics	Solar energy	Non dispatchable source of power
11	Solar-thermal	Solar energy	Non dispatchable source power supply
12	Bagasse power Plants	Bagasse, steam turbines	Cogeneration for heat and electricity
13	Coal power plants	Coal, steam turbines	Power generation
14	Nuclear – Conventional	Radioactive fission	Base load power
15	Nuclear – Small Modular Reactors	Radioactive fission	Baseload and peak power, non-dispatchable
16	Wave power plants	Sea water and wind	Baseload, predictive
17	Tidal power plants	Sea water and gravitational forces	Predictive, non-dispatchable
18	Diesel power plants	They use diesel cycle	Power generation, automotive

		engines and multiple fuels (HFO, IDO, natural gas, and biofuels)	and marine applications
19	Fuel cells	Hydrogen, biogas, biomethane,	Base load, peak, dispatchable
20	Grid Scale Battery Storage	Chemical energy, alternative power sources	Dispatchable, flexible applications
21	V2G	Storage batteries, alternative energy sources for power	Dispatchable, flexible applications

From Table 20-17, it is noted that various sources of power are unique in characteristics with respect to the grid with some being dispatchable while others are not dispatchable.

20.8. Conclusion

This study assessed sustainability of various sources electricity based on sustainability indicators. The sustainability indicators used were price of generated electricity, full lifecycle greenhouse gas emissions, availability of renewable sources, energy conversion efficiency, land needs, water use, and social economic impacts. The study assumed that each indicator has equal importance to sustainable development and used to rank the renewable energy technologies against their impacts. This study showed that wind is the most sustainable renewable energy resource, followed by hydropower, photovoltaics and then geothermal. The values used for ranking used for relative ranking was provided using data collected from published literature.

Energy is a leading contributor to the climate change, and accounts for about 60% of global GHG emissions. As an emission reduction strategy, renewable energy (RE) generation and integration has been accelerated globally. The wider adoption of renewable energy generation is associated with both positive and negative impacts. It also encounters several economic, social, technical, political, and environmental challenges. To attain sustainable power systems, focus should be placed on key areas like energy efficiency and diversity, social value and public acceptance, power supply reliability, technological innovation, competitive

and cost reflective pricing, market-sensitive interventions, standard requirements, regional integration, and power quality. Successful energy transition requires progress in these areas.

CHAPTER 21:

RESULTS AND DISCUSSIONS

21. Overview

This chapter presents the summary of the research findings in terms of the role of energy in sustainable development,

21.1. Energy and Sustainable Development

Globally, electricity is playing a critical role in the modern life of all countries hence the need to understand how sustainable a country's energy supply and consumption system is and how to attain and maintain electricity sustainability. Through the cumulative effect of the Stockholm, Rio, and Johannesburg conferences, sustainable energy development (SED) was identified as a very important factor in the sustainable development as it linked energy to the environmental dimension in the Stockholm conference, economy in the Rio conference and society in the Johannesburg conference. This study reviews sustainability in electricity production, supply, and consumption in support of the global commitment to mitigate greenhouse gas emissions and global warming. Global electricity generation remains dominated by fossil fuel sources with renewable energy sources contributing a smaller proportion. From this study, it was noted that whereas sustainable development has social, economic, and environmental pillars, electricity sustainability is best analysed by five-dimensional approach consisting of environmental, economic, social, technical, and institutional/political sustainability to determine the resource and power system sustainability. The energy transition requires new technology for maximum use of the abundant but intermittent renewable sources a sustainable mix with limited nonrenewable sources optimized to minimize cost and environmental impact but maintained quality, stability, and flexibility of an electricity supply system.

This study recommends the use of the three main strategies to minimize carbon emissions in the energy transition. These are conventional mitigation, negative emissions technologies which capture and sequester carbon emissions and finally technologies which alter the global atmospheric radiative energy budget to stabilize and reduce global average temperature. Besides low emissions, a sustainable electricity grid system should be stable and supply reliable, affordable, and socially acceptable electricity. A sustainable electricity system needs facilitating technology, policy, strategies and infrastructure like smart grids, and models.

Stringent climate control scenario shows that power generation in developing countries will be about 75% renewables by 2050 while the fossil fuel plants will be fitted with carbon capture systems. With anticipated reductions in the cost of variable renewable energy (VRE) costs, the pace of decarbonisation will be accelerated. However, this progress will only be achieved through a combination of measures like progress in technologies to deal with intermittency e.g., smart grids and decentralised generation, making conventional power plants more flexible; expansion of regional power pools, demand adjustment, adjusting demand and advances in energy storage technology and control. With additional measures like resolving the challenges to regional integration, increased regulatory reliability and development of inadequate power infrastructure, will enable developing countries realise their power grids running entirely on renewables by the years 2050 [3],[2],[40].

The pace of progress towards 100% renewable sources will be influenced by availability of dispatchable renewable power sources like hydro, geothermal, biomass or gas as well as the pace of investment in power system networks. For many countries especially in Africa and Asia classified as developing economies, the power transmission and distribution networks remain rudimentary hence constrain the ability to move low-carbon power from sources to where it is most needed, to import power when domestic renewable output is low, and to export excess renewable energy output when generation is excessive and to integrate energy storage within the power grids [29],[40].

Although decentralised generation offers the potential solutions to use of renewable energy sources, reliable centralised grids are still necessary to meet the needs of many productive enterprises, in urban centres and large scale load centres. A fossil-free grid requires advanced operational capabilities that are not yet in place in many countries. High shares of renewables require advanced grid management capability like sub-hourly dispatch and intra-hourly scheduling, automatic power generation control (AGC), weather and plant power forecasting techniques and advanced energy storage infrastructure which is institutionally and operationally demanding. Charging requires regulatory models that reward batteries for charging in periods of high renewable energy generation output and discharge when it is low. While markets should provide incentives through differential pricing for the V2G and G2V systems. Suitable regulatory models that support integration of energy storage is still work in progress even for developed countries. Developing countries won't achieve their development aspirations, in terms of the SDG 1 (to end poverty), SDG 7 (to attain universal

access to reliable energy) and SDG 8 (realise decent work and economic development) without largescale expansion of reliable and affordable grid electricity[2, 40].

Developing countries should be supported to achieve their self-determined, least cost power sector development plans and decarbonisation plans in the long-term under the Paris Agreement. Accelerated decarbonisation requires the investments in fossil fuel substitutes, support regulatory and market reforms, energy storage, power transmission at national and international level, and improved power network management capabilities[40, 1089]

21.2. Energy Sources and Role in the Transition

21.2.1. Biogas

Biogas is competitive, viable, and generally a sustainable energy resource due to abundant supply of cheap feed stocks and availability of wide range of biogas applications in heating, power generation, fuel, and raw materials for further processing and production of sustainable chemicals including hydrogen, and carbon dioxide and biofuels. The capacity of biogas-based power has been growing rapidly for the past decade. The study identified various pathways for use of biogas in the energy transition by application in power generation and production of fuels. Diesel engines, petrol or gasoline engines, turbines, micro turbines, and Stirling engines offer feasible options for biogas to electricity production as prime movers. Biogas fuel can be used in both spark ignition (petrol) and compression ignition engines (diesel) with varying degrees of modifications on conventional internal combustion engines. In internal combustion engines, the dual-fuel mode can be used with little, or no modification compared to full engine conversion to gas engines which may require major modifications.

Biogas can also be used in fuel cells for direct conversion to electricity and raw material for hydrogen and transport fuel production which is a significant pathway to sustainable energy development. Enriched biogas or biomethane can be containerized or injected to gas supply mains for use as renewable natural gas. Biogas can be used directly for cooking and lighting as well as for power generation and for production of Fischer-Tropsch (FT) fuels. Upgraded biogas/biomethane which can also be used to process methanol fuel. Compressed biogas (CBG) and liquid biogas (LBG) can be reversibly made from biomethane for various direct and indirect applications as fuels for transport and power generation. Biogas can be used in processes like combined heat and power generation from biogas (CHP), trigeneration, and compression to Bio-CNG and Bio-LPG for cleaned biogas/biomethane. Fuels are manufactured from biogas by cleaning, and purification before reforming to syngas, and

partial oxidation to produce methanol which can be used to make gasoline. Syngas is used in production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process[62].

Biogas is an attractive source of renewable energy mainly due to its huge biomass potential, globally. Significant quantities of biomass is dumped in landfills, while some is left in the agricultural fields as the rest is disposed of in unauthorized areas leading to environmental degradation from uncontrolled anaerobic digestion[437, 728]. The huge, biogas potential globally and many feasible biogas to energy conversion technologies, have positioned biogas at the forefront of the global energy transition options[341, 1090]. Microbial-controlled biogas production has a significant role the global carbon cycle where we have a natural anaerobic biodegradation estimated to generate 590–800 million tons of methane into the global atmosphere [468, 769]. Bioenergy sector continues to receive significance attention due to extensive usage like biogas production, with Germany having about 9000 farm scale biogas digesters are in operation[1091]. Biogas is a sustainable energy resource that can be produced from any biomass including waste. Biogas technology can be applied to convert various biomass into methane-rich biogas, which is carbon neutral alternative to fossil fuel sources like gas, diesel, paraffin, and petrol. Additionally, anaerobic digestion has benefits like solid mass reduction, decreased odor, reduced low emissions, alternative income or revenue source as compared to conventional waste treatment systems [929].

Biogas is a renewable energy carrier used in electricity and heat production, and as a transportation fuel. Most biogas is produced from anaerobic digestion of sewage sludge at waste water treatment plants. Other raw materials include manure and food industry wastes. By substituting fossil fuels, biogas has significant environmental improvements. By generating 1 MJ of electricity from biogas, is equivalent to consumption of fossil energy between 0.4 and 0.9 MJ. Other than direct environmental benefits, the indirect benefits include changing land use and treatment of organic waste products. Use of biogas as opposed to fossil fuels in heat and electricity production decreases the greenhouse gas emissions (GHG), by 75–90%. This reduction in emissions increases further when the digestate is used in place of chemical fertilizers. When manure or food industry wastes are employed as raw materials for biogas production, the highest reductions in GHG emissions are achieved. The acidification and eutrophication potentials reduce by up to 95% by use of biogas. Use of biogas increases photochemical oxidant creation potential by 20–70%. [697].

Therefore, biogas use is a strategy to control several serious environmental problems, like eutrophication, acidification, air pollution and greenhouse gas emissions. Proper design and location of biogas systems can maximize the potential benefits, and reduce potential negative effects[697].

Studies show that using biomethane as vehicle fuel can reduce greenhouse gas emission reductions of 27–62% as compared to emissions from conventional natural gas passenger vehicles or 41–70% compared to conventional petrol vehicles. The main challenge is limited suitable biomass to support widespread deployment of power-to-methane systems using biogenic carbon. Available biomethane production options offer attractive means to reduce greenhouse gas emissions in a future energy system with large amounts of intermittent renewable power generation[1092].

Several have been carried out aimed at evaluating the life cycle environmental impacts associated with the power generation from biogas produced by anaerobic digestion of agricultural products and waste. Studies on the anaerobic digestion using tomato waste, maize silage, slurry, and tomato waste as feedstocks and for cogeneration applications suggested that systems using animal slurry offer best options, except for ecotoxicity to marine and terrestrial environment. The studies also indicate that it is more feasible to have smaller plants that use slurry and waste rather than big plants using maize silage to operate efficiently. Electric power from biogas is environmentally more sustainable than grid electricity for many biogas schemes. However, compared to natural gas, biogas electricity is not always the best option in terms of impacts. Biogas also has higher impacts than other renewables, like solar photovoltaics, wind and solar. Overall, though, biogas electricity can help minimize the GHG emissions relative to a fossil-intensive electricity mix, although some other impacts may increase. Further analysis shows that, if the main objective is to mitigate climate change, then other renewables like wind, solar and hydro offer greater potential to reduce GHG emissions than biogas. However, by cogeneration where heat is used, the environmental sustainability of biogas will significantly improve particularly in terms of the global warming potential, summer smog, and the depletion of ozone layer and abiotic resources. Avoiding open digestate storage minimizes methane emissions while regulating digestate spreading onto land help minimize emissions of ammonia and related environmental impacts[944].

Biogas has a significant role to play in the impending energy transition as a renewable and sustainable energy resource because of its high energy conversion potential and the

widespread availability for power generation, industrial applications as a renewable process feedstock and for thermal energy applications[107, 109, 110, 341, 410]. In addition to producing biogas, the anaerobic digestion (AD) process leads to feedstock treatment during the treatment phase, and it can also produce digestate, which is a useful organic fertilizer that can replace chemical fertilizers in sustainable agriculture [608, 1093]. An essential part of the global carbon cycle is the creation of biogas through microbial control, as natural anaerobic biodegradation releases 590 to 800 million tons of methane into the atmosphere annually [107, 437, 441]. Numerous different organic feedstocks are anaerobically digested to produce biogas, which can then be enhanced to produce natural gas such as biomethane[468]. The sustainable technique of turning biomass waste into biogas can lead to advantages including less carbon emissions, improved organic waste management, and increased resource use efficiency [107, 1094].

In terms of efficiency and cost, Stirling engines and internal combustion engines theoretically offer the most viable options for converting biogas to electricity, particularly on a small scale[28, 30, 34]. The electricity generated by internal combustion engines per kilowatt hour is cost competitive and efficient, while the engines are available in a wider range of sizes, they are more flexible and efficient, and they require less effort to operate and maintain[275, 386, 495]. For slightly larger plants, gas turbines are commonly utilized for power generation in the range of 3 to 5 MW. Turbines generally and microturbines less stringent fuel quality standards requirements compared to internal combustion engines[101, 279, 299]. This makes them ideal prime movers for raw biogas which has wide range of harmful impurities[96, 442, 1095]. Both the steam turbine and the gas turbine power systems for converting biogas to electricity encounter higher total capital investment costs [141, 158, 794, 1096, 1097]. Including enhanced biogas, biogas and biomethane provide a way to include rural businesses and communities in the transition of the energy industry. This is accomplished by creating grid-connected electricity and reducing grid load by generating their own electricity and heat[284, 926].

Biogas as an energy resource has the potential to contribute to sustainable the sustainable energy transition if carefully produced through the process of anaerobic digestion of organic substrate under carefully regulated conditions and used in a manner that limits leakages of methane which is a greenhouse gas[470, 480].. The energy content of biogas is contingent upon the methane composition, which is subject to influence from both the production process and the type of substrate employed. The composition of biogas may include elements

like Sulphur, which can make it inappropriate for use as a fuel in internal combustion engines and certain industrial chemical and thermal processes. The calorific value of biogas demonstrates variability because of its composition, primarily influenced by the relative abundance of methane. The heating value of biogas generally falls within the range of 21-23.5 MJ/m³, suggesting that an approximate equivalence of 0.5-0.6 liters of diesel fuel or roughly 6 kWh of electricity can be attributed to 1 m³ of biogas [386, 387, 1098].

Biogas has significant potential as a sustainable and renewable energy resource, both currently and in the foreseeable future[64, 322]. Biogas energy can make a substantial contribution to the achievement of sustainable development goals and the global transition towards sustainable energy, because of its minimal greenhouse gas emissions, widespread availability, and access to raw materials. It widescale incorporation of biogas into the global energy and electricity mix has been constrained due to presence of harmful impurities and low calorific value of raw biogas[12, 769, 923, 1090]

21.2.2.Biomethane

Biogas upgrading involves purification processes aimed at increasing methane content of biogas that is like natural gas. The environmental assessment, based on the Life Cycle Assessment (LCA) method, of different upgrading technologies will help in the identification of the environmental characteristics of biomethane and improvement measures. The LCA of biomethane production from waste feedstock, using the SimaPro software comparing several upgrading technologies like membrane separation, cryogenic separation, pressure swing adsorption, chemical scrubbing, high pressure water scrubbing and the on-site cogeneration of electricity and heat, that include environmental benefits derived from the substitution of fossil-based products. Indicate a better environmental performance of the cogeneration option. Studies show an average improvement of close to 76% compared to conventional cogeneration. Membrane upgrading technology shows the best environmentally convenient results compared to other biogas upgrading methods [941, 942].

Biogas upgrading by removing CO₂ and other contaminants enables biogas fuel to attain the specifications required for injection in the natural gas grid and application as fuel for vehicles. The process facilitates conversion of wet biomass into a perfect substitute of natural gas. Biogas upgrading involves the removal of CO₂ using various techniques, but the most diffused method is water scrubbing. The CO₂ can also be directly recycled into methane through a high-temperature co-electrolysis process followed by methanation to increase

biomethane yield. The environmental impacts of two pathways for biomethane production compared in the framework of the Life Cycle Assessment (LCA) methodology shows that due to high electricity demand, the electrolytic process where electricity source is not close to 100% renewable is unfavourable [943].

Studies were carried out by [942] on the environmental and economic aspects of common biomethane production methods namely membrane separation, chemical absorption with amine solvent, water scrubbing, and pressure swing adsorption a life cycle perspective using data from the Italian existing plants. The results of the study showed that all the biogas upgrading options are fully sustainable, and in particular, the membrane separation technique showed the best performances, although in some cases with little differences [942].

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Biogas upgrading to biomethane consumes about 20% of the biogas energy using existing conversion technologies mainly in compression. [927]. is a summary of the well to wheel greenhouse emissions from biomethane and fossil fuels.

Table 21-1: Well To Wheel (WTW) GHG emissions in g CO₂eq/km[927]

	Fuel type	WTW emissions CO ₂ eq/km	g	Remarks
1	Petrol/gasoline	164.0		Has high environmental impact
2	Diesel	156.0		Cleaner than petrol
3	Compressed natural gas (CNG)	124.0		Cleaner than petrol and diesel
4	Bio-CNG (20%)	100.0		Less impact than natural gas
5	Bio-CNG (100%)	5.0		Cleanest

From it is noted that biomethane has the least environmental impact based on the WTW values of petrol, diesel, compressed natural gas when used as a fuel substitute for fossil fuels namely petrol, diesel, and natural gas.

Studies of the current state biomethane production suggests a current production potential of more than 1.9 billion m³/yr, with commercial initiative in Europe alone being more than 645, in 2017, most of them being in Germany. Way forward into the future new biogas plants will have to be equipped with upgrading units, that will foster cost reduction and a parallel consolidation of the operation plants availability. Biomethane production is projected to grow and reach 18 billion m³/yr in 2030; based on improvement of already installed biogas plants, with increased use of feedstock like municipal solid waste (MSW.) This potential is about 10% of natural gas projected demand for the EU's in 2030[919]

21.2.3.Producer Gas

Producer gas is produced by burning combustible biomass with an air deficit and a in an environment of air deficiency and regulated amount of humidity to produce a gaseous. a mixture of hydrogen, carbon monoxide, carbon dioxide, and nitrogen, hydrocarbons like methane. Producer gas has a lower heating value (LHV) of 5, 800 KJ/m³. Producer gas is used as an industrial fuel for iron and steel manufacturing e.g., firing coke ovens and blast furnaces, cement, and ceramic kilns, or for mechanical power and running gas engines for

heat and power generation. In the gasification process used, organic material like biomass is burnt at relatively low temperatures (1292° to 1832° F).

Gasification is used to turn biomass resources into gaseous compounds (producer gas or syngas). Gasification of biomass resources can produce bioenergy and bioproducts ideal for dual-mode engines to produce power (e.g., for irrigation) and to produce heat, steam, and electricity. Biomass gasification technologies can also be used to produce hydrogen, organic chemicals, and ethanol which have significant applications as fuel cars and trucks and to extend its use as a source of electricity while hydrogen can be used as a clean energy carrier and fuel in fuel cells for transportation, heat, and power generations.

Therefore, producer gas production through gasification is a sustainable way of utilizing combustible biomass, clean the environment, prevent uncontrolled methane production and emissions, and produce clean and renewable energy for the energy transition.

21.2.4.Syngas

Syngas also called synthesis gas is a mixture of carbon monoxide (CO) and hydrogen (H₂), which is the product produced by high temperature steam or oxygen gasification of organic material such as biomass. Syngas can be used for production of organic molecules like synthetic natural gas (SNG-methane (CH₄)) or liquid biofuels such as synthetic diesel using the Fischer-Tropsch synthesis but needs cleaning to remove impurities like tars. Therefore, syngas production can be used to dispose of solid biomass and be used as a renewable and clean fuel for steam, heat, and power generation.

21.2.5.Bagasse

Sugarcane bagasse is a by-product of milling sugarcane and it is an important fuel resource for the sugar industry used for steam and power production. Bagasse is a fibrous, has low density material and has a wide range of range of particle sizes with high moisture content. Sugarcane bagasse (SCB) is among the most abundant agricultural residues globally in over 100 sugar producing countries globally. Bagasse is mainly used as a fuel for cogeneration by the sugar factories, but has other applications like ethanol production, paper and pulp manufacture, biogas production and charcoal briquettes manufacture. The falling electricity prices and reducing global sugar prices due to excess sugar stock in the world market have made bagasse a very attractive fuel for grid-based electricity generation and supply making it a feasible diversification pathway for sugar factories. This study identified various physical,

chemical, and thermodynamic properties of bagasse and sugar cane trash as fuels in the sustainable energy transition.

This study recommends various policy initiatives to promote the use of bagasse and cane trash as a fuel particularly in heat and power generation. Proposed measures include attractive feed in tariffs for cogenerated heat and power, tax incentives and measures to encourage investment, and a flexible power purchase agreement that recognizes the unique challenges facing the sugarcane manufacturing like unsteady supply of cane and hence inconsistent milling and fuel supply. Bagasse has various pathways for exploitation as an energy resource i.e., direct combustion in boilers to produce heat for steam and power generation, anaerobic digestion to produce biogas and pyrolysis and gasification to produce syngas. Syngas and biogas can further be upgraded to produce biomethane which has significant energy and process applications as a substitute of natural gas. Bagasse has got three major components, namely pith, fiber, and rind.

21.2.6. Hydrogen

Today the global hydrogen market is estimated at US\$ 130 billion growing at an average of 9% per year driven by the growing demand for renewable energy sources with countries rich in renewable electricity being attractive to the green hydrogen. Hydrogen is the most abundant element on the universe. Hydrogen is a combustible element whose products are heat and water making it one of the cleanest combustible fuels. However, most hydrogen produced globally is grey or blue derived from fossil fuels mainly natural gas[1099].

Green hydrogen which currently accounts for less than 1% of global hydrogen production is produced by electrolysis using renewable electricity. Most of the green hydrogen produced is used in energy intensive industries like steel and chemical production. The main challenge facing green hydrogen production is high cost of production which makes it noncompetitive with significant release of carbon dioxide which is a greenhouse gas[1099].

The benefits of green hydrogen are many and include the fact the hydrogen is green and renewable and can be produced locally and hence reduce dependence on imported fuels. Hydrogen is versatile and can be stored and transported and hence provide a solution to the challenge of intermittence[1099]. Green hydrogen can play an important role in sectors that are hard to decarbonise like aviation and heavy metal industry[1099]. The sustainable energy transition requires that most of the hydrogen produced should be green hydrogen. This requires investment in infrastructure and cost reduction to make it more competitive.

21.2.7.Wind Energy

As an energy resource, wind is clean, renewable, and inexhaustible, and is pollution free. The main challenge with wind energy is that it is non dispatchable and unpredictable. For this reason, wind is used often as a means of saving conventional sources of energy and must be used when it is available. Wind is also widespread and cannot be concentrated over a small area for exploitation hence may have significant land requirements based on desired capacity to generate sufficient power[1100].

Power available in wind is a function of the cube of velocity making wind speed very important. Another important factor is the swept area.

Power developed = $13.14 \times 10^{-6} AV^3$ kW.

Energy produced by a wind power plant is therefore affected by altitude of the site or turbine and the velocity duration curve.

The velocity of wind increases with height from the ground and hence the higher the level from the ground the higher the wind velocity and hence the power[1100]. The changes in wind velocity over time significantly affects the power produced. The actual energy in available in wind and the energy available in steady wind varies considerably and it depends on the actual shape of the velocity duration curve. There wind power generation is done within wind velocities mainly to overcome friction and other resistance for minimum speed and to avoid damage at extremely high wind velocities. Typical wind speeds for viable sites are 30 to 45km/hr. Wind turbines are designed for a rated wind speed for which the power output is maximum, hence the correct turbine should be selected[1100].

21.2.8.Solar Energy

The earth receives close to 1.6×10^{18} units of energy from the sun annually which more than 20,000 times the energy requirements of man on earth. This energy is used in photosynthesis and evaporation of water in the water cycle which causes rains. Man harnesses a negligible fraction of the solar energy. Although solar energy exploitation remains relatively expensive compared to fossil fuels, the non-renewable nature of fossil fuels and global concerns over fossil fuels related emissions provide incentives for investment in solar technology while advances in technology have improved the competitiveness of solar derived power[1100].

21.2.9.Coal

Coal is the world's largest single source electricity accounting for over 40% of global electricity production and close to 77% of fuel-based electricity in south Africa and recent projections indicate that coal will continue to be the country's primary source of electricity into the distant future. Several environmental concerns are associated with use of coal like large land surface areas and pollution of water bodies by coal mining operations, air pollution, related accidents and damage of transport infrastructure as well as contribution to global greenhouse gas emissions that cause global warming [1100, 1101].

The use of coal in power generation is a heavy burden for the social and ecological systems that are far beyond the prices of electricity. By accounting the life-cycle externalities of coal-derived electricity conservatively doubles to quadruples the electricity price which ultimately makes renewable energy like wind and solar more attractive and feasible options.[1101]. The use of carbon capture and sequestration can increase sustainability of coal for continued by reduced use while a fuel shift from coal to cleaner natural gas and finally biomethane in the long run can be a sustainable pathway for coal use and substitution.

21.2.10. Heavy Fuel Oil and Industrial Diesel

It is estimated that the world's oil reserves will run out by 2047 whilst natural gas will run out by 2068 with coal is in a better situation being exhausted by 2140 while Uranium would run out by 2144. Which implies that the world should develop more sustainable options to substitute and complete the fossil fuel sources of energy [1102] Heavy fuel oil (HFO) also known as bunker fuel or residual oil which has a tar-like consistency is remnant from the petroleum distillation and cracking process and is therefore contaminated with several different compounds including sulphur, aromatics, nitrogen, which effectively make it more polluting compared to other fuel oils. HFO is also referred to "the bottom of the barrel." Since it is left when more useful products of crude oil have been extracted. It is preferably used by diesel power plants, diesel engine propelled marine vessel propulsion mainly because of their it's relatively low cost compared to distillate fuel oils like industrial diesel oil[1103, 1104].

The use of heavy fuel oil (HFO) presents several environmental concerns like risk of oil spill and high level emission of toxic compounds and particulates like black carbon. Whose use is currently banned for ships travelling in the Antarctic in line with the International Maritime Organization's (IMO) International Code for Ships Operating in Polar Waters

(Polar Code) with similar measures being considered for Arctic waters is currently being considered[1103]. Nevertheless, developing countries like Kenya continue to use heavy fuel oil in their diesel engine power generation.

The environmental consequences of heavy fuel oils can be more prolonged because of heavy fuel oil are significant and include the threat to vulnerable marine life such as seabirds and commercially sensitive resources that may last longer in the event of a heavy fuel oil spill[1103]. HFO can also be toxic, if other waste products are added to the fuel, even though generally the lighter fractions of crude oil have higher overall toxicity. HFO is more environmentally hazardous than other fossil oils since it is slow to disperse and break down in the environment and tends to form tar lumps in marine waters, particularly in colder regions such as the Arctic. Studies show that lighter fuel would disappear from the surface of water within 3 days mainly through dispersion and evaporation while HFO will still be present after 20 days, since emulsification significantly increases in volume. The high viscosity of HFO slows down its degradation, and tendency to emulsify and sink into the water column and the seabed. For colder polar regions, HFO can also be caught up in ice and moved over great distances[1103].

Strategies emission related strategies for HFO and other fossil fuels a fuel switch, engine modification, and use of end-of-pipe technologies which include cogeneration although they may not necessarily reduce the life cycle emissions. A shift from heavy fuel oil to natural gas like LNG may not decrease the global warming potential by more than 8–20 per cent, although the reduction depends on the magnitude of the methane slip from the gas engine. [1105]. There are however significant operational benefits in the shift from HFO to natural gas as shown in the research to convert Kipevu III power station from HFO to natural gas and the installation of a cogeneration system to generate extra power in the studies done for Kipevu III and Kipevu I diesel power plants in Kenya. All this research is part of this study from which we can observe that fuel shift to natural gas can add value to the energy transition.

21.2.11. Natural gas

Natural gas remains the fastest growing primary energy source globally and is the cleanest burning petroleum-based fuel. However, the global market is much smaller than for oil on account of transport sector application since it is difficult and costly to use natural gas in the transport sector. The CO₂ emission of NG is lower than all other fossil fuels which making it

a favourable fuel in terms of the greenhouse effect. Natural gas also has very positive contribution on both the environmental pollution and on economic aspects [20] Replacing coal powered generation with natural gas has significantly contributed to the emissions reductions in the power sector but raises questions about the, but the near- and long-term roles for natural gas under deep decarbonization strategies. Natural-gas-fired generation can reduce the cost of power decarbonization, a result that is robust to a range of sensitivities, when policy measures allow carbon removal. [21]. Utilities planning for net-zero targets that can include plans to build gas-fired capacity, need to establish sustainable levels for easy and economic retirement e consistent with electric sector decarbonization goals [21]

Natural gas is compatible with net-zero emissions goals on condition that policy allows a net-zero policy that allows power plants with CO₂ capture and removal offset. Studies which foresee stranded natural gas power plants being stranded assets in a zero-emissions future often assume that policies will adopt a Carbon-Free framing rather than a Net-Zero one. Use of new and existing natural gas enabled by carbon removal as part of a net-zero power sector will help in the reduction of CO₂ emissions, reduce the cost of decarbonizing the power sector and enable reliable power system operations, and. The role of a net-zero system hinges on carbon capture, either directly (through gas with CCS) or indirectly (through carbon removal to offset unabated gas or through CCS for blue hydrogen) [21]. Additionally, substitution of natural gas with biomethane once biomethane market becomes cost competitive will reduce the risk of stranded assets in the transition.

The deployment and use of natural is guided by policy, technology, and market uncertainties.[21]. Countries with higher costs for natural gas and other fuels and with limited CCS deployment infrastructure due to CO₂ transportation and storage challenges will find it difficult to deploy more natural gas I the net zero strategy [21].

21.2.12. Nuclear Energy

The nuclear power industry has grown significantly since the commissioning of the first power reactor in 1944, since by 1972 there were more than 100 nuclear power reactors globally with combined capacity of over 30 GW[1100]. The sustainability analysis has placed nuclear energy among the most sustainable energy resources with huge Uranium reserves, highest energy density, among the cleanest in both direct and lifecycle assessment. However, the greatest limitations affecting nuclear energy are concerns over safety, nuclear proliferation, huge capacity, and capital investment requirements.

The development of modularised SMR reactors which are below 300 MW in capacity is transforming the nuclear energy and power industry by increasing the flexibility, reducing size and capital cost requirements and ability to develop stepwise in phases. These reactors are more sustainable than the conventional reactors and have addressed many limitations of the nuclear energy industry and are expected to play an important role in the energy transition.

21.2.13. Hydropower

Waterpower or hydropower represents a form of energy that is inexhaustible since it is naturally replenished by the action of the sun that evaporates water to form clouds which then comes back as rain. The main challenge with hydro power is seasonal variability and scarcity of commercially viable sites in some geographical locations and is also affected by the climate change. The dispatchability of hydropower depends on the type of power plant or conversion system used and whether or not a dam and reservoir are provided which can significantly affect its sustainability in terms of environmental impacts [1100].

21.2.14. Geothermal Energy

Geothermal energy is the heat from the earth which can be exploited for thermal and electricity generation applications. The temperature of the earth increases at an average of 1°C for every depth of 35 to 40 which implies that it is hot enough to boil water at a depth of 4 km and at a depth of 15 km, the temperature is about 1000 to 1200 °C.. The thermal gradient is significantly high in some areas like those where magma is close to the surface and in regions near the tectonic plate boundaries. These factors affect the relative distribution of economically viable geothermal energy sites globally[1100].

Geothermal energy remains one of the least objectionable energy resources but has minimal contribution to the global electricity generation capacity, but it remains a very important source of local energy.

21.2.15. Tidal power

Man has known and used tidal power also called lunar power since time immemorial for applications like milling, irrigation, and sawing of firewood. Tides are caused by combined effect of the gravitation of the moon and the sun on water on the earth's surface. Spring tides are tides with maximum range obtained when these gravitational forces combine while the neap tides which are of minimum range are obtained when the two gravitational forces oppose. On average about 705 tidal cycles are obtained per year[1100].

Many feasible sites have been identified globally as feasible for tidal energy exploitation for power generation. Notable sites include La Rance in France, Severn Barrage in the UK, the White sea in Russia, Passama-quoddy in the USA, the Gulf of Cambey in India with maximum tidal range of 10.8 m and Gulf of Kutch in India having a maximum spring tide of 7.5 m[1100].

21.2.16. Wave Power

Wave energy is contained in waves which typically measure 2 to 3 meters high thought the year. The energy content of a wave is per square meter surface area is obtained from the equation

$$E=1/2\sigma g\alpha^2$$

Where

σ is the density of the sea water,

g is the gravitational attraction

α is the wave amplitude

For the Atlantic Ocean, the average wave period T is 9s average propagation velocity is 14 m/s with observed power flow of 70kW per meter of wave front. Hence a 1200 km coastline has close to 84 GW power[1100].

Wave power is one of the non-conventional energy sources widely spread over the water bodies. The non concentrated nature of wave energy pauses challenges in its exploitation. The prospects of wave energy would significantly improve if technologies or means are developed to efficiently and cost effectively collect the energy spread over extensive areas of water and concentrate into a smaller volume for exploitation[1100].

21.2.17. Magneto Hydrodynamic Energy

The principle of operation of a magneto hydrodynamic power system is based on the Faraday's law of electromagnetism. According to this law, an electromotive force (emf) is induced in a conductor in any state e.g., gas, liquid or solid that moves in a magnetic field. Magnetic hydrodynamics refers to the study of the dynamics of electrically conducting fluids that are in interaction with a magnetic field[1100].

21.2.18. Ocean Thermal

The Ocean Thermal Energy Conversion (OTEC) system, is employed in tropical ocean waters and takes advantage of the difference in temperatures between solar-heated surface water which is usually at 24°C to 30°C and cooler, subsurface at about 1000 m depth whose temperature is 4°C to 8°C. A closed-cycle OTEC system makes use of warm seawater to heat and vaporize a working fluid like e.g., ammonia, which expands and spin a turbine for power generation. The cold sea water is pumped from depth through a condenser to condense the working fluid vapour back into a liquid which is then recycled through the system.

An open-cycle OTEC system works by vaporizing warm surface water itself which is the working fluid in a near vacuum at the temperature of the surface water to spin a low-pressure turbine. The cold deep water condenses the vapour to water freshwater since salt was lost upon evaporation. During cooling the vapour, the cold seawater gets warmed to a temperature between its original temperature and the surface water temperature. To avoid temperature anomalies, heated effluent is returned deep into the ocean about , 60 m to protect aquatic life from adverse environment [1106].

21.2.19. Ocean Osmotic

Osmotic power, or salinity gradient power or blue energy refers to the energy available because of the difference in salt concentration between seawater and fresh water or like water. There are two methods used for this i.e. electro-dialysis (RED) and pressure retarded osmosis (PRO) both of which rely on osmosis with membranes.

The global energy potential for osmotic energy is about 2000 TW h. However despite demonstrating significant energy potential to meet global energy demands, the technologies need further research and development for large-scale deployment[1107]. A Nano fluid device can be used to convert the Gibbs free energy of mixing to electricity as an energy harvesting method. Whenever two solutions of different salt concentrations are separated by a porous membrane, ions are driven through the pores from a higher salt concentration side to the lower salt concentration side. If the pores are charged, the electrostatic interaction between counterions and the pore surface tends to hinder their passage, making them ion-selective. This leads to asymmetric ion diffusion generating a net ionic current flow through the pores, and a cross membrane osmotic potential is developed. This process is called osmotic energy conversion, characterized by electricity produced. where two reservoirs with salt solutions at different concentrations are separated by a porous membrane having

charged nanopores. The diffusion of the ionic species from the high salt concentration through the nanopores to the low salt concentration side induces a net diffusion current is induced, converting Gibbs free energy of mixing to electricity[1108].

21.2.20. Biomass

Biomass refers to materials originating from once living organisms that can be utilized for energy production [34]. Sources of biomass include oil palm, sugar cane, and others [1088]. The methods for converting biomass to energy, include direct combustion and gasification. [1109].The challenge with biomass energy is distribution throughout which requires energy in transportation, competing application with other biomass applications like the soil stabilization fertilizer and erosion control, use as animal fodder and other uses. Generally, up to 35% of crop residues can be removed from the land without adverse effects on soil structure and fertility, but the entire crop residue can be used in this way. About 10 to 50% of total agricultural residues can be used for bioenergy production [1109].

Various feed stocks are available for biogas production ranging from, harvested, and processed biomass sources of energy to products from natural forests, as well as human and livestock wastes. Biomass also has negative impact to the environment e.g. burning wood fuel and crop residue in the fields generates carbon dioxide which can be offset by photosynthesis in fast growing energy trees or well-managed forest cover since trees absorb carbon dioxide as they[64]. The rate of destruction may however exceed regeneration leading to unsustainable biomass use with negative impacts like desertification and in atmospheric carbon dioxide. Other negative impacts of bioenergy crops are displacement natural ecosystems, soil degradation, and also water resources consumption while synthetic fertilizers used have some notable carbon value. About 1/3 of wood used globally is unsustainably harvested and consumed. Bioenergy also requires energy for harvesting, drying, and transport to power stations and processing facilities which add the carbon footprint since greenhouse gases produced [1110], [29]. According to [576], the use of biofuels should be limited to application of unavoidable biomass residues and synthetic fuel sources to avoid competition between fuel and food crops in order to achieve full sustainability.

21.3. Energy Sources for Grid Power

Table 21-2: Summary of energy options for the global transition

Energy resource	Features and composition sustainability	Contribution to the transition and sustainability
1 Hydropower	Hydropower is renewable and is gotten from moving water which runs hydraulic turbines. Hydropower is affected by weather	Hydro has contributed clean power for many years. Significant potential remains in small and mini hydropower schemes in decentralized and centralized generation. Use of storage facilities like dams and pumped storage plants will enhance their use generation
2 Solar Energy	Solar is a variable renewable energy supplied by natural radiations from the sun. the energy is affected by weather and may be unpredictable intermittent in some cases	Solar will play a big role in the future transition as a renewable energy resource but development in solar cells technology and smart grids will enhance their uptake contribution to grid electricity. Energy storage and transition to smart grids will enhance their use in electricity generation
3 Wind Energy	Wind is natural and renewable and can be developed as onshore or offshore wind power stations. The main challenge facing wind power is variability and intermittence as well as large land requirements.	Wind resources are significant but variable in supply. there huge contributions lie in the transition to smart grids and development of energy storage facilities. Wind power is clean and abundant although variable and intermittence. Smart grids and energy storage will improve their uptake and contribution.
4 Hydrogen	Hydrogen can be made by electrolysis and mainly by steam methane reforming	Hydrogen will play a leading role in development of fuel cells and as a fuel to replace fossil fuels. More research into efficient conversion and handling is needed to generate hydrogen from renewable sources as opposed to use of fossil fuel

			gases.
5	Bioenergy	Include biogas, biofuels, energy crops, plant waste, animal waste. Relevant policy measures necessary to make them competitive	Renewable and zero and low carbon sources and can substitute fossil fuels domestic, industrial, transport and power generation. Bioenergy sources include biogas, syngas, gasification, bagasse, bioethanol, biodiesel and other fuels and energy sources of organic origin including energy crops.
6	Geothermal Energy	Geothermal energy has significant potential but huge upfront costs, investment risks and long project delivery tools have kept contribution low	Geothermal has very low actual and lifetime emissions. Has high load factors and capacity factors and hence ideal for base load electricity supply, Increased use of geothermal will reduces electricity price, reliability and cut on greenhouse gas emissions. Use of wellhead generators can help mitigate some shortcomings like cost and project duration.
7	Waste to energy	Huge quantiles of animal, plant, and combustible industrial wastes most with significant energy potential are produced continuously globally. They include municipal solid waste, agricultural waste, and animal waste like slaughterhouse waste	Various waste to energy technologies exists with more efficient systems being needed for efficient waste to energy conversion. Processes like biogas and biomethane production, direct combustion can be used both for a clean environment, generate green energy ad electricity and reduce disposal costs and health risks in a sustainable manner.
8	Nuclear energy	Nuclear power takes many years to develop, guarantees large supply of low carbon electricity at	Nuclear will increase reliability, reduce unit cost of power, and cut on emissions. There is need to increase funding for nuclear energy and reduce the high project duration.

		high load factor and capacity factor. Also, unit cost of power is relatively low.	Use of small modular reactors for countries with low demand and to facilitate phased development is encouraged for faster growth of nuclear power.
9	Marine energy	This is renewable energy resource mainly in form of tidal power, wave power and ocean thermal. Ocean thermal is limited by the low thermal gradient over which heat transfer is to take place.	Has very limited contribution globally by will lay a leading role in the transition by investing in efficient technology for extraction of energy with low thermal gradient in ocean thermal. Policy incentives and funding is necessary to increase generation from wave and tidal power. The main challenge with marine power is that supply is not continuous, but relatively predictable.
10	Fuel cells and energy storage	Fuel cells renewable based on the source of hydrogen or energy and oxygen. They have over 99.99% system reliability	They will increase the use of variable renewables like wind and solar, and hydro by absorbing and storage energy for use during the peak and when the supply diminishes
11	Natural gas	Natural gas is nonrenewable source but cleaner than coal, diesel and petrol and global resources are huge	Can substitute heavy polluters like coal and petroleum like diesel and petrol as fuel. The main challenge is delay in the transition to zero carbon target and investment risk involved with the transition.
12	Coal	Coal is nonrenewable and currently the largest source of global electricity. Huge reserves in some countries. Generate ash and carbon dioxide, N ₂ O and SO ₂ hence high environmental	Coal produces reliable power but has high emissions. It can stabilize generation. Consumption should gradually reduce by substitution.

		impact	
13	Other fossil fuels (Diesel and petrol)	Generate high carbon emissions as well as N ₂ O and SO ₂ . High reserves in some countries hence slow transition	With application of efficient generation like cogeneration and blending, can supply limited power and fuel for use

From Table 21-2, it is noted that both renewable and nonrenewable sources of energy have a role to play in the energy transition. The nonrenewable sources like coal and oil are abundant in several countries and therefore are readily available and offer energy security. The steady release of energy by fossil fuel sources is important for reliability and stability and hence quality which are sustainable energy requirements. However, their high carbon footprint, finite supply, price and supply interruptions and resource related conflicts make fossil fuels unreliable and unsustainable source of energy and hence the need for gradual substitution with renewable and low carbon sources of energy. The use of highly efficient conversion technology and clean coal as well as carbon capture and sequestration can greatly reduce the carbon footprint of fossil fuel sources. For natural gas, controlling leakages along the entire supply chain is paramount due to the high global warming potential of methane which is the main constituent of natural gas.

Solar and wind offer the greatest potential but suffer from unpredictable and unreliable supply challenge hence the need for advanced energy storage facilities. For grid electricity, the unreliability and unpredictable supply nature of wind and solar is a danger to energy security and the grid stability for the traditional grid. However, the use of smart grids with ability to absorb small-scale producers and variable supply will greatly increase the absorption of wind and solar energy as well as small hydro sources and decentralized generation.

21.4. Transition Enabling Technologies and Concepts

21.4.1.Introduction

The energy transition requires various technologies, infrastructure and concepts which include the smart grids, distributed generation microgrids, energy management systems, the demand side and behind the meter management [3, 1111]. By using smart grids instead of the

traditional grid helps in maximizing the integration of renewables, enable use of smart appliances, support distributed generation and related storage, electric cars and their charging infrastructure including V2G infrastructure, automation of power transmission, and distribution, and improvement of energy efficiency among other[1112],

Many strategies or methods can be applied to reduce carbon emissions and achieve the global energy/electricity transition [61, 1112, 1113].

Distributed Generation (DG) of electricity offers solutions like high efficiency and environmental protection, reduced transmission, and distribution losses, and improves system stability. Distributed generators integrate with renewable energy technologies which are locally available like photovoltaic systems, wind power, small hydro turbines, tidal, biogas, etc. [1111, 1112]

21.4.2.Summary of Technologies and Concepts for the Energy Transition

The sustainable energy transition requires enabling technologies, policies, concepts, and strategies besides availability of sustainable energy sources. These are summarized in Table 21-3.

Table 21-3: Summary of sustainable energy transition strategies

Strategy	Impact of the strategy	Remarks
Electrification of transport	Will reduce the consumption of fossil fuels used in powering engines in cars, trains, and trucks	The electricity for use should come from predominantly renewable and low carbon sources like nuclear, wind, solar and wind. Development in energy storage and a resilient electricity grid is necessary.
Electrification of transport, industrial and domestic processes, and systems with clean electricity	Reduction in fossil fuel consumption for powering industrial boilers, furnaces, and process equipment	Research and development of efficient heating systems, reduction in unit cost of power increased use of renewable and low carbon electricity is a requirement.
Use of clean and renewable fuel in	Will reduce dependence on fossil fuels like diesel,	Need for policy measures to promote production and use of biofuels like

place of fossil fuels	petrol, heavy fuel oil and	ethanol, methanol, biogas. Research in efficient combustion systems is also necessary as well as competitive biofuel pricing.
Energy conservation and efficiency measures	This reduces the actual energy consumption and hence emissions, and effectively delays expansions and related investment costs.	Reduces emissions by cutting down consumption but new efficient methods and systems must be developed.
Decentralized generation	Will increase local generation and encourage cogeneration, trigeneration and generation from renewable energy sources	This requires modernization of the grid to absorb small producers and allow two-way communication between consumers and producers. With possible variable pricing
Transition to Smart grid	Smart grid will allow active participation of the utility firms, producers and consumers allowing consumers also to sell power and choose when to use power	With smart grid more variable renewables will be absorbed but requires investment and modernization. Peak shaving is made possible by moving consumers from peak hour to off-peak consumption through variable pricing
Use of modelling simulation and decision support tools	Modelling and simulation tools are computer-based planning and simulation tools that facilitate accurate long range, short term and Realtime planning of electricity generation resources	With use of modern modelling and simulation tools, optimum use of energy generation and supply infrastructure will be made which will improve efficiency, effectiveness, reduce costs and emissions simultaneously both in real time and in the long term
Carbon capture and sequestration	Carbon capture and sequestration can be done using natural means or industrial scale carbon dioxide and other emissions capture, storage, and burial	Carbon capture requires development of efficient technology and policy measures to make it viable and attractive.
Cogeneration and trigeneration	Improves efficiency	Cogeneration and trigeneration requires simultaneous demand for electricity, heat and cooling
Earth and Solar Radiation Management	This involves use of climate geoengineering techniques to reduce the global temperature. reducing solar incoming radiation.	Geoengineering schemes which use solar radiation management technologies help modify terrestrial albedo or reflect incoming shortwave solar radiation back to space provide an alternative solution to the challenge of global warming.

Demand Side	
management	
Energy markets	
Legal and Policy	These are non-technical
Measures	measures meant to
	enhance the energy
	transition

From Table 21-3, it is noted that various technological strategies can be adopted separately or in combination to reduce emissions and hence achieve a sustainable energy transition. They include electrification of transport which requires efficient and cost-effective energy storage systems and a resilient electricity grid to handle multiple variable consumer and supplier load. This creates the need to transition from the traditional grid to a more resilient smart grid. Electrification of the rural populations that are not electrified also provides an opportunity for increased use of renewable sources of electricity especially through decentralized generation systems. The use of decentralized generation will widen feasible grid connected generation which mostly comes from renewable energy sources. Energy efficiency by consumers will reduce demand and wastage, hence avoid emissions while efficiency in generations leads to less fuel consumption and hence emissions and reduced environmental impact. Although fossil fuels are major contributors of greenhouse gas emissions leading to global warming, most of them are price competitive, have steady release of energy hence the power plants operate at high load and capacity factors with high reliability of electricity supply, and thus provide grid stability. Therefore, their consumption now and soon is key to a stable and reliable electricity grid which is a key requirement of energy sustainability. The consumption of fossil fuels should be reduced but they will continue to supplement the intermittent and unpredictable but abundant wind and solar energy which have the key to the future sustainable energy supply in a highly optimized electricity generation and supply system where technology will play a key role in planning and decision support. The carbon footprint of fossil fuels used in power generation should be minimized by adoption of efficient conversion technologies like cogeneration and trigeneration to minimize which reduce fuel consumption and maximize generation from limited energy resources. Other technologies include dual fuel diesel power, use of biofuel

substitutes fuel blending with biofuels and use of combined cycle powerplants. Therefore, a sustainable transition for now should involve an increase in energy efficiency to reduce the total demand and wastage of fossil fuels in an optimized system in which the grid absorbs all variable renewables. The smart grid and advanced storage technologies will play a significant role in the sustainable electricity transition.

From this study, the technical options to the energy transition can be grouped into three categories. They are substitution technologies, carbon capture and sequestration and climate geoengineering techniques.

21.4.3. Transition from Traditional to the Smart Grid

The energy transition towards sustainable energy systems requires advanced technologies like smart grids, management systems and renewable energy generation and storage. To manage operation of such complex systems requires the integration and coordinating several power system components like advanced sensors and smart meters as main data sources in the era of big data, wireless communication, and application of the internet of Things (IoT) [314, 315]. Such data acquired should be stored, processed, and analyzed to generate the necessary output for efficient deployment of smart grids and operation of power stations demand and supply while integrating renewable energy and clean sources of energy and demand side management options. Very important in a modern power system is energy fuel efficiency, reduction of emissions and waste minimization[2, 3]. The benefits from such a modern grid include better asset management, enhanced operations planning, better monitoring and control, reduced cases of voltage instability, accurate prediction, and fault detection in a power system. Such advanced system also faces several challenges in implementation related to aspects like data uncertainty, data security, data quality, and data complexity[314, 315].

The electricity grid is undergoing significant changes because of the proliferation of variable renewable energy resources, intelligent sensors, high-speed signal processors, among other developments. Smart grids (SG) can be said to be modern electric power grid architecture having higher efficiency and dependability. Smart grids present the greatest potential advances in the global sustainable energy transition[21, 562]. Smart grids were proposed as a result of rapid growth in demand and users thus the need for efficient distribution of the electricity, reduced losses, high quality and reliability, and high security of electricity supply[12, 563] Energy transformation and sustainability is a global challenge, for many developing countries, facing energy-related issues like wide demand–supply deficiency, over

dependency on fossil energy sources, and low access to clean energy. The smart grid technology has ability to address these challenges and support a smooth transition from traditional to smart energy systems [3, 56, 62]. The power grid consists of transmission lines, substations, transformers and other meant to deliver electricity from power plants to end users [61, 73]. The grid usually consists of many power plants of different technologies and characteristics, networks, generators, grid operators and different stakeholders applying different communication levels. The coordination in traditional grids, is usually manually controlled[2, 326]. The smart grid uses intelligence for integration of user actions connected to the system like consumers, generators, and other stakeholders for delivery of sustainable, economic, and electric power [3, 61, 564]. A smart grid makes use modern communication and computer technology to operate and control the electricity network to better handle potential power system failures[12, 61, 565]. Therefore, a smart grid is equipped with advanced communication, automation, and information technology systems (IT) that enable real-time bidirectional monitoring and control of electricity and information between sources of power and consumer appliances.

There is a global transformation of the traditional power system that is unidirectional in structure and operation to a configurable and participatory two-way structure where actors or participants can interact with one another [3, 61, 74]. The main motivation for this transformation is advances in communication, power electronics, and computer technology and increasing need to accommodate the variable renewables and electric cars on the power grid while maintaining. maximum reliability, quality of service, with minimum economic and ecological costs, while maintaining maximum safety for equipment and users and always keeping the voltage and frequency values within the permitted range [12, 96, 559].

The traditional electric power grid technology is over 100 years old, and its design is meant to feed electricity from large central power plants using high voltage network, covering considerable distances to deliver power to end users via lower voltage distribution network with little flexibility[12, 61]. Over years now, electricity demand has grown rapidly mainly due to social-economic development and industrial growth but the supply mainly comes from cheap traditional sources of energy like coal, gas and petrol that are associated with release of greenhouse gas emissions (GHG) to the atmosphere that are responsible for climate change[62, 112]. The electricity grid is being modernized towards advanced consistency, less costs, and greater efficiency through more uptake of renewable energy, advanced control technology and two-way communication. There has been a growing need for substation

modernization to cope with fast growth of the grid, growing consumer needs, and technological innovations leading to grid transformation. The Smart grid can help accomplish these technological reforms across the grid in power generation, transmission and distribution, through more use of sensors, communication and computers[65].

Therefore, a smart grid marks a shift from centralized power generation to decentralized power generation. Smart grids seamlessly integrate the three power system functions of generation, transmission, and distribution are integrated evolving the grid into integrated smarter system. The smart grids facilitate the integration of all forms of power generation and converts a consumer into a producer and consumer (prosumer) enabling households to generate and store electricity both for sell and own use courtesy of the two way power flow and communication facilities[566].

The smart grid can empower customers with real-time control and the choice between storing, generating and consuming electricity based on prevailing cost, availability of energy and demand for electricity. Through demand response (DR), smart grids enable customers to change their electricity consumption pattern by shifting or reducing their consumption from peak to off-peak hours thus making power flow more interactive, efficient, customer friendly and more environment friendly[566]. The concept of smart grid is an addition to existing or prospective smart meters which allow accurate energy flow analysis for power utilities, increase uptake of renewable energy sources and facilitate sharing of energy with increased system throughput[567]. The modern should simultaneously address the challenges of increasing environmental pollution, greenhouse gas emissions, and diminishing of fossil fuel reserves and climate change[68]. Smart grids facilitate decentralized decision making and enable active participation of prosumers and other assets not owned by the grid. They additionally facilitate monitoring of energy flows, manage prosumers' energy supply and demand changes which may be rapid to attain local energy balance, and optimize the electricity flows in the power systems[568].

The traditional grid was designed to connect far away consumers of electricity from central power plants using a rigid one-way power flow arrangement. On the other hand, smart grids are designed to provide a two-way flow of power and information. This has been made possible by developments and advances in information technology, communication and power electronics technology making it possible to accommodate new energy carriers, as well as decentralization of power generation, and higher uptake of variable energy sources like wind and solar and variable loads like electric vehicles. This will enable higher access to

electricity over and beyond the capability of the traditional grid [3, 21, 62]. Today, an ideal electricity grid ought to be a two-way system with power generation from a mixed multitude of big, medium and small, distributed plants supplying grid power in an optimized mix mode [106, 569]. This will facilitate maximum and optimum absorption of variable and intermittent renewable sources of energy like wind and solar have huge potential to contribute to the grid as sustainable and renewable energy sources needed for the global energy transition[3, 21, 58, 110].

21.4.4.Decentralization of Generation

21.4.4.1. Microgrids

Microgrids are sections of an electric grid with the ability to disconnect from the main grid and operate autonomously, to supply own loads from local energy sources for some period. Microgrids could cover a small town, neighborhood, a hospital, military barracks, a school, university campus etc. Some microgrids are permanently independent of the main grid [1114]. A typical microgrid consists of.

- i. A microgrid switch for connection and disconnection from the central grid.
- ii. Local or internal energy sources
- iii. A microgrid controller is used to control and optimize system resources.
- iv. Some form of energy storage

A microgrid is said to be “islanded” when it is operating separately from the central electricity grid. Islanding by a microgrid can be necessitated by a grid outage or poor grid power quality. In this case, the microgrid helps the central grid in its healing while at the same time it provides quality and reliable power within its microgrid system. This ability enables the renewable energy resources within the microgrid to continuously operate and supply power even during times of the main grid outages. Therefore, microgrids are especially beneficial in countries where the quality of power and reliability of the grid is low. Energy storage capability is important for a microgrid designed to operate in island mode for smooth transition without power loss to loads when the central grid experiences an unplanned outage[1114, 1115].

Microgrids can significantly alleviate some burdens of the utility because of the presence of local power sources and its ability to control voltage and frequency. A microgrid having variable renewable sources manages own variability making it unnecessary for the main utility to deal with local variabilities. A supervisory controller of the microgrid is used to

decide which microgrid energy resources to operate at what time what times to achieve balanced load and generation. This microgrid controller may consider predicted price profile, predicted load profile, predicted wind, solar power profile, predicted load like heating or and cooling needs, predicted emissions levels and other parameters in its scheduling which makes intelligence a key capability requirement for a microgrid. Other functions of the microgrid controller include change the operating modes of power resources, provision of power setpoints to resources, or regulation of droop characteristics [1114].

A microgrid switch is also equipped with an intelligent controller to decide when to perform islanding and connection functions. For applications where reliability is valued highly like hospitals, some factories and military installations, use of alternative sources of energy with one or two diesel or natural gas generators are relatively although they are not historically referred to as microgrids. The modern concept using more complex microgrids containing multiple sources of power and controlled for purposes beyond reliability are not common though[1114]. Generally, where power supply is reliable, microgrids may not be typically justified economically, unless reliability is seriously valued highly. For jurisdictions or areas with less reliable power systems, microgrids easy justify economically[1114, 1115].

21.4.4.2. Virtual Power Plants (VPP)

Virtual power plants (VPP) are an aggregation of energy sources that can be treated as a single larger energy resource from the point of view of a power grid. Virtual power plants are therefore like microgrids except that the resources may not be geographically co-located and often have no ability to operate independently from the central power grid. The definition of a virtual power plant may vary, but they are generally defined as an energy system using any combination of renewable power sources, conventional power sources, energy storage and distributed resources (DR). The operation involves the use of a central controller or aggregator to coordinate the different resources in a way that they are treated as a single resource from the grid operator's perspective [1114].

Because a VPP does not need special hardware or intelligent switchgear and can draw from resources distributed throughout a power grid, a VPP is typically less expensive to implement than a microgrid. In fact, because VPPs are tied together by software controls, a given VPP may last for only a short length of time (a year, a month, or less than a day) and can be easily and inexpensively modified. [1114].

An aggregation of DR resources configured to be reliable and dispatchable can form a virtual peaking power plant without adding any actual generation. This type of VPP has been piloted in the U.S. Energy prices based on real-time bulk electricity generation costs are rarely transmitted to customers, but VPP operators can access wholesale prices and pass them on to DR and other re-sources without direct involvement from grid operators. This allows more efficient use of grid resources without complicating utility operations. An aggregation of renewable resources can also act as VPP, as has been piloted in Europe 10[1114].

21.4.5. Energy Storage

The intermittence and variability of variable renewables like wind and solar as well as variable loads introduces significant stability challenges to the grid and limits the grid integration of variables. A potential solution to this challenge is the integration of a fast-response energy storage system which is an important component with great prospects in future power systems and for its role in alleviating the problem of supply-demand balance in power systems. This enhances self-consumption and offers an opportunity to reduce energy costs while at the same time increasing the uptake of the renewables by the grid [595].

Grid-scale storage has a very important role to play in the Net Zero Emissions by 2050 Scenario, by providing services like short-term balancing and operating reserves, ancillary services needed for grid stability and deferment of investment in expansion or extension of the grid, to long-term energy storage and restoration of the grid after a blackout. The most widely used storage technology is pumped-storage hydropower, while batteries have emerged as the most scalable type of grid-scale storage with a strong market growth in recent years. Other energy storage technologies available are compressed air and gravity storage, but their applications remain minimal. Hydrogen is another emerging storage technology with significant potential for seasonal storage of renewable energy [1116].

21.4.6. Waste to Energy

Waste-to-Energy (WtE) is an attractive value addition as well as waste management option. Waste to energy technologies provide valuable energy, reduce cost of waste disposal, and help greenhouse gas emissions from fossil fuel energy sources. Waste like municipal solid waste can provide energy directly or can be used as refuse derived fuel[34, 495]. Waste-to-energy (WtE) or energy-from-waste (EfW) is a process used to generate energy as electricity and/or heat from the primary treatment of waste, or production of fuel from waste.

Many waste to energy systems generate electricity and/or heat directly through combustion or production of combustible fuel, e.g. methane, ethanol, methanol, pyrolysis oil from plastic or synthetic fuels. Energy recovery from waste generally involve conversion of non-recyclable wastes into useful heat, electricity, or fuel through processes like combustion, gasification, pyrolysis, anaerobic digestion and landfill gas recovery. [93, 164, 360]. Important waste-to-energy technologies include combustion of solid wastes for cogeneration like bagasse cogeneration by the sugar industry and recovery of pyrolysis oil from waste plastics [1117].

The main barriers to successful deployment of waste to waste-to-energy systems, are economic, technical, operational, and management challenges. Majority of biomass based wastes are currently landfilled which is wasteful use of potential energy resources [489]. Anaerobic digesters are ideal for high moisture-content organic wastes. Anaerobic digestion for biogas and biomethane production has significant potential for food waste-to-energy municipal waste digestion and agricultural waste. There is growing number of systems operating on mixed food waste at central locations and large food producers[279, 320, 489, 1118]

21.4.7.Power Plants and Role in the Transition

A power plant refers to an assemble of equipment for generation of electricity to given quality and specifications from a given energy resource. Power plants have different characteristics and often use unique energy resources to meet the changing electricity demand/load which can be classified into base load, intermediate and peak load.

21.4.7.1. Diesel Power Plants

Diesel power plants are designed diesel cycle internal combustion engines. Although the diesel engines are designed to run on diesel fuel, they can be run on other fuels with or without modifications based on fuel characteristics. Diesel power plants are used mainly to supply peak and emergency power demand and rarely for baseload demand due to high operating costs, high fuel costs and their ability to start and stop quickly corresponding to changing demand often during the peak hours.

It was established in this study that the sustainability of diesel power plants can be enhanced by using cogeneration or combined cycle to exploit the significant exhaust heat in the engine exhaust to generate steam for extra power generation to the tune of about 10% using the Rankine cycle, but more can be produced using more efficient cycles like the binary.

Converting diesel engines to run on dual fuel mode or pure natural gas or biomethane can also increase sustainability by reducing greenhouse gas emissions and generation cost since natural gas is generally cheaper and cleaner hence lower operation and maintenance costs.

21.4.7.2. Coal Power Plants

Coal still accounts for most of the global power generation and is also responsible for most of the energy sector related greenhouse gas emissions. Coal rich countries and regions enjoy socioeconomic benefits related to coal mining like jobs and higher economic activity close to coal activities and a source of energy security to the coal producing countries. The energy transition seeks to minimise the use of coal as an energy resource as a strategy to achieve the global emissions and climate targets. In the middle term, substituting coal power plants and uses with cleaner natural gas is an option, though not a permanent measure.

This study identified coal to natural gas use and use of carbon capture and sequestration as strategies to limit coal related emissions in the energy transition.

21.4.7.3. Gas Turbines

Gas turbines have grown in applications in power generation ever since the first gas turbine was used in a central power station in 1939. The gas turbines plants have limited space requirements for the same capacity as diesel and steam power plants and are extremely quick to start and stop hence ideal for peak power and emergency power supply. They have high fuel flexibility and can burn a wide range of fuels, both renewable and non-renewable fuels mainly natural gas and kerosene[1100].

21.4.7.4. Nuclear Power Plants

Nuclear energy is a clean resource mainly exploited through fission reaction of Uranium. The main challenges facing nuclear energy and power generation is high capital cost, long project delivery period energy, challenges in handling nuclear waste and huge capacity and limited operational flexibility. Nuclear energy technology is constantly developing with the development of more efficient reactors and small modular reactors being the latest innovations in the nuclear energy sector. The small modular reactors are efficient in combating climate change and in bringing the needed flexibility to electricity generation for a more electrified society with opportunities for cogeneration making nuclear power more efficient and sustainable [1119, 1120]. Commercial nuclear power plants are based on the controlled fission reaction of Uranium-235 in a reactor. Uranium is non-renewable radioactive which is available in many countries globally. Uranium can be used in natural form or can be enriched

in enrichment facilities. Larger reactors are needed for power plants using raw uranium compared to those using enriched uranium[1100]. Being emission-free and reliable energy form, nuclear plays an important role in the vision to build a cleaner world. Small modular reactors as a part of are part of future of nuclear power, in the sustainable energy transition [1119, 1120]

Nuclear power plants with capacity below 300 MW are called small modular reactors. The main difference with conventional big nuclear power plants is their lower power output and ability to be serially produced. They can generate carbon-free energy more efficiently, more flexibly, and at a lower cost than the conventional power plants. SMR reactors vary in size from tens of megawatts up to hundreds of megawatts, and can be used for applications like power generation, process heat, desalination, or other industrial uses and constitute a major strategy to develop safe, like power affordable nuclear electricity options. SMR designs may employ light water as a coolant or other non-light water coolants like liquid, gas, or molten salt[1119, 1120]..

Advantages of SMRs include their relatively small physical footprints, lower capital investment, can be sited in locations not possible for conventional nuclear power plants, and provisions and allow incremental power additions. The small modular reactors (SMRs) also offer distinct safeguards, security, and nonproliferation advantages[1119, 1120].

21.4.7.5. Wind Power Plants

Wind turbine generators come in different designs and sizes with the selection being done based on specific site conditions and applications. The wind turbine with the propeller rotating around a horizontal shaft in a plane perpendicular to the wind flow direction is the most widely used type due to significant economic benefits. The propeller often consists of 2 to 3 blades with aerofoil that can be as wide as 60 m on a tower that can be as high as 305 m.

Generation occurs when wind rotates the wind vanes or propellers that are coupled to a shaft which rotates a generator to produce electricity. Savings can be achieved at with uninterrupted supply of power to customers by operating wind generators in combination with conventional plants like diesel or steam plants leading to fuel savings as customers shift to wind when wind power is available[1100]

Wind power becomes viable where cost of conventional power transmission and delivery is high and in cases where continuous power supply is not essential. Wind power often require

some storage to store generated power that is not needed for later use which increases the installation and running costs.[1100]

21.4.7.6. Solar Power Plants

Solar energy is available in almost all countries, is clean and renewable. The main challenge for solar energy in the energy transition is the high initial costs and its variability and intermittence which requires the use of storage that effectively increases costs. Through continuous research and development, the costs for modern solar technologies are currently cost competitive with conventional technologies. With grid scale energy storage, the intermittence can be addressed. Due to its abundance, cleanliness and renewability, solar energy will play a very important role in the sustainable energy transition. Further cost reductions and increase in conversion efficiency, better storage technologies and higher capacity factor will significantly increase the sustainability of solar energy.

21.4.7.7. Hydro Power Plants

There are different power plants varying in terms of applications, location, and topographical features, presence of storage, and the head of water for the power plant. Based on operation, hydropower plants can be classified as base load, peak load, and pumped storage hydropower plants. Based on the head, hydropower plants can be classified as low (less than 70 m) , medium (between 70 and 300 m) and high head power plants (above 300 m)[1100].

21.4.7.8. Bagasse Power Plants

With over 115 countries classified as sugar cane producers, bagasse has established itself as a sustainable energy resource for use by sugar cane factories to produce their needed thermal and electrical power while exporting excess to the grids to earn them extra revenue and play an important role in stabilising electricity grids through decentralised generation with significant socioeconomic benefits like sustaining the competitive sugar industry and creation of local jobs. With over 1.8 billion tons of cane production globally, close to 600 million metric tonnes of bagasse fuel is produced annually for use in cogeneration.

21.4.7.9. Geothermal Power Plants

Various cycles have been developed for geothermal power generation. These systems can be classified based on the turbine used and the type of thermodynamic cycle applied in conversion of thermal to electrical energy. In indirect systems also called the binary, the geothermal fluid is not allowed to have direct contact with a steam turbine. Instead, a heat exchanger is used to transfer the heat to a low temperature boiling organic fluid which

evaporates and expands in a turbine or expander to generator mechanical power to rotate the generator for power generation[1100].

In direct conversion systems, dry steam or separated steam from a flashing system is directly used to run a condensing turbine while in some cases the exhaust is released to the atmosphere. Dry steam plants operate with steam coming directly from the well while flash steam power plants are used where the steam is wet and requires the flash chamber to produce dry and clean steam to run the turbine.

The main challenge facing geothermal power plants is long project delivery period which can be solved by use of temporary or permanent wellhead generators. The power plants operate at high load factors hence ideal for base load power supply. Operational challenges include long starting time for a well that shuts down and risk of sand and debris damaging the turbine blades[1100].

21.4.7.10. Fuel Cells

Fuel cells convert the chemical energy of in fuel mainly hydrogen efficiently to electricity without combustion. The process has significantly low emissions with water as the main product of the reaction compared to conventional equipment/techniques that are associated with greenhouse gas emissions. The three main parts of a fuel cell assemble are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions travelling via the electrolyte. At the cathode ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit. Fuel cells development partially focuses on optimization of catalytic the layer of the catalytic electrodes, and by reducing metal without appreciable loss of the fuel cell performance. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by amount of reagent available. The theoretical efficiency fuel cells is about 90% while in thermal engines the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60%. which is still significantly greater than efficiency of combustion engines. The fuel cells operate with continuous replenishment of the fuel, and the oxidant at active electrode area and with no need for recharging. The elements of a fuel cell are the electrode, an oxidant or an air electrode, and an electrolyte. Common fuel cells used are hydrogen, oxygen (H_2 , O_2), hydrazine (N_2H_4 , O_2), carbon/coal (C, O_2) methane (CH_4 , O_2). Hydrogen-powered fuel cells emit only water with virtually no pollutant emissions. On the other hand, fuel cells powered by hydrocarbon-based

fuels have the potential to Employing hydrocarbon-based fuel inevitably leads to CO₂ emission. Since fuel cells are not subject to the limitations of the Carnot cycle efficiency, fuel cells attain higher efficiency that can be more than twice the efficiency of internal combustion engines.

The transport sector operates with fuel cells having efficiency of up to 65%, compared to 25% for internal combustion engines. Application of heat produced by in fuel cell's reaction for in combined heat and power (CHP) systems, increases overall efficiency to over 85%. Although fuel cells have significantly higher conversion efficiency compared to the internal combustion engines or and gas turbines across their output power range making them ideal for a variety of applications ranging from mobile phones to large-scale power generation, their largescale adoption is limited by high cost and lower reliability. The key to sustainability of fuel cells revolves around the production of hydrogen, the efficiency and capacity factor of fuel cells relative to other renewable sources of energy as well as the size of the installation.

21.4.7.11. Wave Power Plants

Several devices can be used to exploit wave energy including floats, flaps, converging channels, and ramps. A salter cam with efficiency of about 75% operates by simulating the action of a vertical flapping plate at the wave front where energy is absorbed. To avoid disturbing water below as it rotates, the rare of the salter device is cylindrical. The slater is asymmetrical in shape hence it requires counter balancing as its response depends on the prevailing loading conditions[1100].

Another important wave energy conversion system is the Masuda system of floating buoys. The Masuda system uses an air-filled bell-shaped chamber. The air is pumped through a turbine by the rising and falling action of water in a wave. Large installations require many floating buoys to increase the output. A submarine cable is needed to deliver wave power onshore where electricity can be transmitted to a substation. This power can then be inverted and supplied to the grid system.

An alternative application is to use power produced in on board floating factories. The electricity produced can also be used to produce hydrogen for various application. Another feasible application pathway is hydraulic transmission, then temporarily store before transfer to a turbogenerator. The conversion system is preferably inside cams and the power outputs can be connected to a floating substation [1100].

21.4.7.12. Tidal Power Plants

Tidal power plants operate by exploiting a rapidly varying water head using turbines that can operate efficiently under varying head conditions like the Kaplan turbine and propeller turbine whose blade angles can be altered to operate efficiently under varying head conditions. The bulb turbine is particularly ideal for use in tidal power generation by acting equally efficient as a pump and turbine. The bulb turbine which is a horizontal turbine has a steel shell that completely encloses the generator coupled to the turbine runner. The bulb turbine is mounted in a tube within the barrage structure completely submerged. During times of low electricity demand, and rising tides, the bulb turbine pumps water to the basin from the sea basin. When electricity demand is high, the bulb turbine acts as a generator[1100].

France has two operate tidal power plants namely the 9 MW plant at Saint Malo and a 240 MW plant having 700 m long dam at the mouth of the Rance River. Further development of tidal power plants is limited by costs even though more than 50 feasible sites have been identified globally. More sites will become feasible in future with technological advances in tidal power generation[1100].

21.4.7.13. Steam Power Plants

Steam generating power plants are equipped with boilers for steam generation. The boilers come in different designs, efficiency and applications based on fuel used and quality of steam desired as well as cost and efficiency of steam generation. The steam is used to run steam turbines or steam engines for electricity generation. Efficiency of steam power plants is increased by installation of waste heat recovery systems which extract heat from flue gases like the economiser for preheating feedwater, superheaters which generate superheated steam by extracting heat from flue gases and air preheaters which extract heat from the flue gases for preheating combustion air to increase the combustion efficiency. Waste heat extraction in steam power plants reduces environmental impact and increases the steam rate and hence generation capacity of a power plants. Different types of combustion fuels are used for steam generation, and can be liquid, gas or solid fuels e.g., coal, bagasse, nuclear, heavy fuel oil, diesel, natural gas, biogas, biomethane, producer gas and hydrogen[1100].

Besides waste heat recovery the efficiency of steam power plants can be used enhanced by cogeneration (combined heat and power) or trigeneration which involves generation of heat, power, and cooling or cold. Such systems, condensate recovery and use of steam traps. These

measures increase power density, reduce unit cost of power and environmental impacts of power generation[1100].

The common elements of steam plants are the boiler or steam generator, the steam turbine, the economisers, air preheaters, super heaters, feed water pumps, condensers while common auxiliary systems include the fuel handling and storage systems based on fuel used, water treatment plants, the flue gas cleaning systems like electrostatic precipitators cooling water systems, generators, and turbine governing systems. Stea power plants can play a leading role in the energy transition by increasing fuel diversity, efficiency and reducing environmental impacts through measures like steam and fuel recycling and flue gas cleaning to trap pollutants to limit pollution and net emissions by different energy sources like coal[1100].

In a conventional steam plant combustion energy of fuels is transferred the steam which acts as the working fluid. The thermal energy in steam is then converted to mechanical energy in a steam turbine then to electrical energy through a generator mechanically coupled to the steam turbine at an overall efficiency ranging generally from 37 to 40%[1100].

21.4.7.14. Magneto Hydro Dynamic (MHD) Power Plants

In a magneto hydrodynamic power plant, hot gases that are partly ionised at a temperature close to 2500°C are passed through a magneto hydrodynamic (MHD) system duct in which a strong electromagnetic is applied. The gases form an electrically conducting conductor moving across a magnetic field. This induces a direct current emf and current which can be collected at suitable electrodes and transmitted[1100].

21.4.8.Power Plants and Conversion Systems

The various power plants and energy conversion systems for power generation are summarised in.

Table 21-4: Power plants and energy conversion systems for power generation

	Category/type of power plants	Characteristics and Applications	Description and application in the transition
1	Diesel power plant	Use diesel cycle engines as prime movers and diesel, heavy fuel oil (HFO) and industrial diesel oil (IDO)	The engines can be modified to run less polluting natural gas, biomethane, biofuels and use efficiency measures like cogeneration to produce more power

2	Gas turbine power plants (Open cycle)	Mainly use fossil fuels and ideal for peak and emergency power	Convert the open cycle to dual cycle (combined cycle) and use renewable fuels
3	Gas turbine power plants (Combined cycle)	Ideal for intermediate and peak load power supply	Use renewable fuels in place of the fossil fuels
4	Geothermal (conventional)	Ideal for base load power supply and operate at high load factor	Use more efficient cycles like binary cycles instead of less efficient dry steam and flash power plants
5	Geothermal (wellhead power plants)	Available in small modular sizes up to 15 MW	Can be used for quick delivery of geothermal power during steam field development and as independent permanent power plants in decentralized generation
6	Hydro power	Highly flexible and efficient for use as baseload, intermediate and peak power supply	Increase use of small and micropower generation in decentralized generation alongside the conventional power plants which have been in use for hundreds of years.
7	Hydropower (Pumped storage)	Provide the highest energy storage capacity globally	Will continue to play a leading role in balancing load for variable renewables and peak power supply
8	Nuclear (conventional)	Conventional nuclear power plants operate at very high load factor and are ideal for supply of baseload power. They are however limited by huge capital investment cost and large capacities	Nuclear power is low carbon and sustainable energy and will continue to play a leading role in the energy transition. The gestation period and size can be addressed by developing the small modular reactors for quick and phased deployment
9	Nuclear (Small modular reactors)	SMRs are small up to 300 MW and can be deployed in phases	SMRs are smaller and flexible, have less carbon footprint and can be used in power generation, supply of process heat, desalination, or other industrial uses and will enhance faster deployment of cleaner nuclear power
10	Coal power plants	Coal power plants account for the highest share of global electricity generation and mainly used for base load power	Change from coal to natural gas and biomethane, and use of carbon capture and sequestration are the transition strategy for coal power plants before eventual

			phase out in the net-zero transition by 2050
11	Wind power plants	Wind power plants supply variable and intermittent power to the grid	Wind power plants will play a leading role in decentralized generation, but will require Significant investment in grid scale storage and the smart grid to manage the variability and intermittence
12	Bagasse power plants	Bagasse power plant use bagasse and cane trash and can use a standby secondary fuel during out of crop period in firm power plants	Bagasse fuel is readily available as a green renewable and sustainable energy resource. They will increase the economic and social value of sugarcane factories and generate significant power for the grid as substitutes for fossil fuels like coal, oil, and natural gas.
13	Tidal power plants	Tidal power is highly predictable, and the energy resource is significant.	Tidal power plants will supply highly predictable, but intermittent electricity for the grid. Need for balancing and smarter grids will enhance their role. The technology development is also necessary
13	Ocean thermal power plants	Ocean thermal power plants exploit the thermal gradient between cold deep water and warm surface water of the ocean	The ocean thermal power plants have huge potential to generate base load power for the future grids. However technological advances and investment in infrastructure is required to be realized.
14	Wave power plants	Wave power plants exploit ocean waves to produce electricity. They are however intermittent sources, and the technology is less developed	The power plants have huge potential to produce variable power but further investment in technology and infrastructure is needed.
15	Solar Photovoltaics	Solar photovoltaics generate power direct conversion.	Solar photovoltaics are widely applied in power generation in both grid and off grid application.
16	Solar thermal	Solar thermal power plants operate by concentrating power for steam production which is used to run a steam turbine for power generation.	Solar thermals have significant potential to produce power and heat in a more efficient process. They provide opportunities for electrical and thermal energy storage.
17	Magneto hydrodynamic	MHD power plants are still under devolvement but operate at high	MHD have significant potential to supply base load power and in

system (MHD)	plants	load factor and reliability	decentralized generation. Further investment in technology is however needed to reach maturity
18	Fuel cells	Fuel cells operate like dry batteries but are continuous and do not need to be stopped for recharging, instead they are continuously supplied with the energy source/fuel either hydrogen or hydrogen rich fuels.	Fuel cells have high efficiency load and capacity factors and are hence ideal as baseload power sources for the future great. They will also play a leading role in the transport sector as prime movers. Therefore, fuel cells will form an important link between the hydrogen economy, transport, and power sector.
19	Electric vehicles (V2G)	V2G (Vehicle to grids) system connects the electric vehicles for charging and discharge to the grid	Through the V2G infrastructure, millions of electric vehicles will be connected to the grid and act as secondary sources of power and provide balancing role
20	Grid-scale Storage batteries	The grid scale storage batteries store excess energy from non-dispatchable sources like wind, wave, solar	The storage batteries will play an important balancing role for the grid and act as secondary power plants. Maximum use will however require improvements in capacity and reliability as well as development of the smart grids.

From Table 21-4, it is noted that different power plants are available for current and future energy transition.

21.4.9. Transition Enabling Technologies and Concepts

21.4.9.1. Smart Grids

Smart grids can help in the reduction of carbon emissions in the in-power generation and supply by connecting more renewable energy sources especially the variable renewables like wind and solar, and reduction in greenhouse gas emissions through efficient resource use. Network operators have an obligation to minimize their carbon footprint in their operations and measures used to achieve these include reducing callouts with and associated vehicle fuel usage, reduce and leakage of SF₆ in gas-insulated switchgear besides reducing operation and maintenance costs. This is achieved by provision of faster automated services for operations like real time automated meter reading, automated outage management done remotely with limited site visits by technicians and engineers[1121, 1122].

The traditional grid is undergoing substantial growth which calls for a reliable grid operation and maintenance with a more efficient and sustainable consumption of electricity. As a result,

the conventional power grid is being transformed to a smart grid (SG) which supports a diverse, heterogeneous operating measures and devices like smart appliances, smart meters, and renewable plug-in vehicles, energy resources generation systems. The growing electricity demand, expansion of the grid and high number of generating plants and customers have continuously increased the complexity and challenges of the electricity grid in delivering quality and reliable electricity to end users. These challenges require greater system reliability, improved efficiency, more energy security, cleaner environment, and higher system sustainability which can be achieved by use of smarter electricity grids. The smart grid is a rapidly growing concept in the electricity industry that has potential to transform the use of variable renewables, variable loads and improve energy efficiency in grid power systems. The Smart grid is the direction and trend of power industry development based on the physical grid that combines advanced information & communication technology with operation technology the traditional grid to form a smart system.

The main links covered by the smart grid are power generation, transmission, system transformation, power distribution, electricity consumption and dispatch. The smart grid coordinates the needs and functions of different participants in the grid environment enabling the system to operate on the premise of ensuring system reliability and stability. The smart grid technologies have demonstrated potential to revolutionize the electricity grid by means of two-way communications to improve power system reliability, economy, efficiency, and sustainability in power generation, transmission, and distribution. Smart grids facilitate the optimization of the electricity mix consisting of both renewable and nonrenewable sources by application of computer programs and hardware to manage power generation, transmission and distribution resources, smart grids facilitate optimization of the electricity mix of both renewable and non-renewable energy sources for sustainable power generation and supply through existing power system infrastructure. The smart grid technology is a product of the fourth industrial revolution (4IR) and is necessary to accomplish fastest technological reformations in electricity generation, transmission, and distribution (T&D) because of growing application of computers, sensors, sensors, and communications. In this study current trends and application of the smart grid is enunciated. By plugging the Internet of Thing (IoT) in the traditional electricity grid, the resulting smart grids can optimize energy solutions through flexibility in the management of the diverse energy systems, enhance operational insights, improve maintenance forecasting and self-healing abilities, and create more a more secure and safe power system. The study recommends conversion of the

traditional grid to smart grids as a technical solution with significant financial/economic, social, and environmental benefits in the sustainable energy transition. To realize this, it is necessary to build the institutional capacity and put in place policy measures that promote the development of smart grids this like micro grids, modern energy storage, decentralized generation and development of renewable energy resources and technologies.

21.4.9.2. Decentralised Generation

Distributed energy systems (DES or DGs) also called decentralized generation systems have significant potential to enhance sustainability of electricity systems. Decentralized generation systems are small-scale power technologies generally ranging between 3 kW– 10 MW that are located very close to consumers to provide an alternative or enhancement to the centralized or conventional power system. The DGs are connected directly to the distribution system or on the customer side of the meter which significantly reduces the transmission and distribution losses of the power system. The high consumption of fossil fuels and global commitments to reduction in energy related emissions has generated huge interest in renewable energy resources for use in power generation. This has increased the opportunities of utilizing decentralist generation systems in power generation since most renewable sources of energy are also locally available to consumers. The renewable DG systems may be connected to the grid for peak shaving or as a stand-alone system to serve a particular load or an area. Integrating renewable DGs to the power system has many benefits as well as threats if not well coordinated and integrated into the power system. High penetration of renewables can cause several adverse effects on the distribution systems. like voltage rise, reverse power flow, high line losses, creation of harmonics and reduction in voltage quality. Decentralized power systems units should be designed and operated within limits to maintain optimal quality of the power system There is therefore need for optimal sizing and location of renewable decentralized generation (DG) units in the distribution power system for technical and economic benefits. The penetration of renewable decentralized generation systems is considered as a significant contribution to the world energy and environmental crisis.

The main drivers for decentralised power generation are the need to use more clean and sustainable nature of renewable resources compared to the polluting and limited fossil traditionally used in power generation. State and governmental commitment advance broader integration of renewable energies and enforcement of the clean environmental agenda to mitigate greenhouse gasses emissions and combat climate change are other factors in increasing adoption of decentralised generation. Renewable DGs offer several benefits like

energy sustainability, being emission free, and energy security. Policies and regulations used to support investments in renewable DGs, are renewable development and reinforcement of portfolio standards, use of public benefit funds for renewable energy, application of output-based environmental regulations, development of standards interconnection, application of net metering, attractive feed-in tariffs, and tax incentives.

21.4.9.3. Microgrids

Micro grids constitute the ultimate form of decentralized electricity, heat, and cold supply whose operations separated from the main distribution system i.e., autonomous or connected to the distribution system i.e., grid connected. Grid-connected micro grid can be of help during a system fault, by supplying power to the main distribution system, feeding part of its loads for fault detection and service restoration. Micro grids have emerged as a competitive alternative to the final delivery of energy to consumers in combination with on-site production of heat. Distributed generation grouped in micro grids can introduce a richer set of tools for supply of o heat and power, at higher reliability, security, flexibility, and power quality in the conventional grid. A micro grid is typically managed through a central controller that monitors the system parameters, coordinates energy resources, balances load and controls electrical loads, and disconnects and reconnects of the micro grid to the primary grid. Micro grids with no central controller are not common but are technically feasible, with distributed energy resource having an individual controller and the individual controllers operate in a coordinated manner. Micro grids can be an effective option to increase the energy resilience, by providing a functional electric power system capable of operating independently of the main grid.

A microgrid is said to be smart and small-scale power system equipped with controllable loads, some energy storage system (ESS), and small generation units like renewable energy sources (RES, with ability to operate in islanded and grid-connected modes as allowed by the regulatory agency. A microgrid system is has several protection and control devices which facilitate reliable, safe, and optimal operation like ability to connect with the public grid at the point of common coupling (PCC) and successfully operate in both islanded and grid connected mode. Other than solving extensive challenges of power supply in remote and critical installations, microgrids enable extensive use of renewable energy resources (RES) which helps in mitigation of greenhouse gas emissions. Generally, a single microgrid (MGs) is usually applied at a small scale or at the individual or community level, compared to smart

grids (SGs) which are more complex systems covering much larger scale. Therefore, groups of interconnected microgrids can also be seen as a smart grid (SG).

The main grid usually supplies primary power, while the micro grid provides secondary dispatchable power in the event of a grid failure. Emergency diesel generators can provide power directly to loads in the event failure of the primary grid and the micro grid. Proper design and planning of microgrids is important for them to yield all the advantages of the distributed energy concept for the power systems, both local and the clinked central power system. This calls for a reliability -oriented design for microgrids that utilise a large share of the variable and intermittent renewable energy-based, and power electronics-interfaced distributed energy resources. Experience has shown that the power electronics used are prone to wear-out failure and can potentially have adverse effects on the on the performance of the entire power electrics dominated power system. The many benefits associated with application of microgrids have contributed to their significant growth and penetration in decentralized power generation globally. However, challenges are still encountered with respect to design, operation, and control for both island and on grid mode of operation.

A microgrid is generally defined as a small, local distribution system that incorporate a set of micro sources of energy like fuel cells, microturbines, photovoltaic (PV), energy storage and wind turbines, that are a mix of controllable and uncontrollable loads. A microgrid may or may not be connected to the main electricity grid to operate grid mode or islanded mode. Whenever the main grid experiences disturbances or develops faults the microgrid disengages to operate in island moder thus improving the quality of supply to local customers at a higher efficiency, cheaper and cleaner energy, while at the same time help the main grid to heal thus improve its reliability. Additionally, microgrids provide lower investment cost, help reduce emissions, improve quality of power quality and reduce power distribution cost and losses[1111].

Microgrids are sections of an electric grid with the ability to disconnect from the main grid and operate autonomously, to supply own loads from local energy sources for some period. Microgrids could cover a small town, neighborhood, a hospital, military barracks, a school, university campus etc. The modern electric power systems is undergoing significant transformation and revolution as a result of growing demand of electricity, public awareness and pressure to reduce carbon emissions and fight global climate, increased uptake of variable renewables and variable loads like electric cars, advances in power electronics, communication and information technology enabling a two way flow of data and power, and

increased decentralization of power generation and use[61, 62, 296]. These issues and development have helped in the development of the concept of microgrids which have undergone tremendous development over the last decade, with recent boost from the development of the smart grid technologies[61, 1111]. The global energy transition in electrical energy sector is significantly shaping up from the one-way conventional configuration to the open ended, configurable, flexible, intelligent, and participatory structure that harmoniously accommodates the development of microgrids. The motivation for the transformation varies widely from country to country but generally all seek to achieve widescale electrification and uptake of renewable energy sources for power generation [1123].

21.4.9.4. Electrification of Vehicles

The transport sector accounts for close to 14% of the global greenhouse gas emissions mainly on the account of the use of fossil fuels as energy sources in the form of diesel, petrol and natural gas. Electrification of the transport sector with most of the electricity being generated by renewable and sustainable sources will significantly contribute to the sustainable energy transition. This will be further enhanced by use of renewable fuels like biomethane, biofuels etc as fossil fuel substitutes with grid discharge options.

The V2G infrastructure is a prerequisite for the connection of electric vehicles to the grid for charging and discharge aided by the intelligence and reliability introduced by smart grids and microgrids technologies. Through these facilities, charged electric vehicles will supply power to the grid during peak demand when prices are also favourable, but charged preferably during off peak when prices and electricity demand are low. The smart grids will offer the resilient needed to support the charging and discharge of millions of electric vehicles connected to the grid.

21.4.9.5. Coal to Natural Gas Conversion

This study identified conversion of coal to natural gas as short term to middle term emissions reduction strategy [114, 279]. This however depends on the cost of natural gas versus coal and will only remain viable or attractive if natural gas remains cheaper. Natural gas is referred as a substitute for coal due to its low carbon footprint. Therefore, authorities and government should put in place measures that favour the coal to gas use. The main risk is the risk of having stranded infrastructure in case of earlier transition to net zero and the risk of delaying the transition by investing in natural gas.

21.4.9.6. Diesel to Natural gas Conversion

Diesel engines have wide applications in transport and power generation mainly for peak and emergency power supply[279]. This study demonstrated from the case study of Kipevu III diesel engine power plant that the conversion from diesel to dual fuel engine power plant is both technically and economically viable and thus a recommended transition strategy in the short and middle terms. The conversion from diesel powered to natural gas requires modification of the engine in terms of parameters like the compression ratio, introduction of the mixer, gas storage and handling systems.

21.4.10. Energy Storage Technologies

High penetration of non-dispatchable renewable sources, introduces the challenge in of operational flexibility. As more and more renewables sources are integrated to the grid, energy storage system (ESS) becomes crucial to provide faster response in balancing and grid services which enhances the grid stability. The challenges facing deployment of energy storage includes regulatory and market challenges to be deployed in the power system operation which also hinders the progress towards the decarbonisation of smart grid network. Energy storage systems can act as “Flexibility energy Resources” and can play an important role in the future smart grid network that can help overcome the intermittence barriers. The use of energy storage as a Flexibility Resource will facilitate increased participation of storage in different electricity markets and improve grid flexibility and stability even with high penetration of renewables [1124].

21.4.11. Institutional and Policy Measures for the Transition

The main drivers for decentralised generation are the need to use more clean and sustainable nature of renewable resources compared to the polluting and limited fossil traditionally used in power generation. State and governmental commitment advance broader integration of renewable energies and enforcement of the clean environmental agenda to mitigate greenhouse gasses emissions and combat climate change are other factors in increasing adoption of decentralised generation Renewable portfolio standards require electricity providers to supply a specific amount of electricity from renewable DGs. The use of public benefit funds raised by levying on electricity rates provide funding to promote decentralised generation and use of renewable energy. Application of Output-based environmental regulations which set emission limits to encourage power producers to increase efficiency and control air pollution are other important measures. Development and enforcement of

interconnection standards are technical solutions and technical requirements that facilitate growth of decentralised generation. The developed standard specifies how specify how utilities should treat decentralised systems as well as design and operational requirements.

Net metering rules enhance the operation of prosumers by specifying how they should be compensated for net power supplied to the utility grids and simultaneously pay for power consumed from the grid when they cannot generate enough for own use. To achieve these function, accurate metering for electricity demanded by consumers. Is critical. The feed-in tariff is another policy measure adopted to promote renewable energy development by guaranteeing sufficient long-term payments for electricity locally supplied the grid from DGs. Payments may be in the form of electricity sales and payments for renewable energy certificates. It is important to have cost efficient Feed-in tariff policies that are e cost-efficient to enable rapid deployment of renewable energy and decentralized generation systems that will benefit the entire society including consumers, prosumers, and utilities Globally, the implementing feed-in tariffs is a successful experience to realise economic development and renewable energy targets. Through property assessed clean energy policy, the cost of increased energy efficiency or renewable energy installations is refunded to residential properties borrowers. This encourages property owners to invest in renewable energy improvements. Financial measures applied to encourage development of decentralized generation and use of renewable energy sources include access to grants, loans, rebates, and tax credits to invest in renewable energy.

21.4.12. Technologies and Power Plants for The Energy Transition

Large-scale renewable energy adoption should include measures to improve efficiency of existing nonrenewable sources which still have an important cost reduction and stabilization role. A resilient grid with advanced energy storage for storage and absorption of variable renewables should also be part of the transition strategies. From this study, it was noted that whereas sustainable development has social, economic, and environmental pillars, energy sustainability is best analysed by five-dimensional approach consisting of environmental, economic, social, technical, and institutional/political sustainability to determine resource sustainability. The energy transition requires new technology for maximum use of the abundant but intermittent renewable sources a sustainable mix with limited nonrenewable sources optimized to minimize cost and environmental impact but maintained quality, stability, and flexibility of an electricity supply system. Technologies needed for the transition are those that use conventional mitigation, negative emissions technologies which

capture and sequester carbon emissions and finally technologies which alter the global atmospheric radiative energy budget to stabilize and reduce global average temperature. A sustainable electricity system needs facilitating technology, policy, strategies and infrastructure like smart grids, and models with an appropriate mix of both renewable and low carbon non-renewable energy sources.

Important global targets have been set by the United Nations Sustainable Development Goals (UN-SDGs) for global achievement by the year 2030[53]. This study seeks to reduce the global greenhouse gas emissions by increasing the share of renewable energy sources by enhancing wider access to clean energy and responsible energy consumption spelt out in the SDGs-7, 12 and climate change mitigation SDG-13 that seeks to substitute fossil-fuel energy sources for renewable energy [53].

A good concept of sustainable development should facilitate social equity, prevent environmental degradation, and maintain a sound economic base. There is need for sustainable preservation of natural capital for sustained economic production and equity in intergeneration equity in resource exploitation. Fulfillment of basic health and participatory democracy is crucial in energy resource planning and exploitation to ensure sustainability. Sustainable transition requires governments to use policy instruments and an effective institutional mechanism to deliver working solutions to a sustainable energy future. The three main dimensions of sustainable development are economic, social, and environmental sustainability. However, sustainability in energy resource use and electricity systems has extra dimensions of technical, and political or institutional sustainability.

Humanity has increased the concentration of carbon dioxide in our atmosphere, amplifying Earth's natural greenhouse effect. This is still ongoing and hence a continuous threat to the global environment. The global average amount of carbon dioxide hit a new record high in 2020: of 412.5 parts per million(ppm). The annual rate of global increase in atmospheric CO₂ over the last sixty years is about 100 times faster than previous natural increases like those that occurred at the end of the last ice age about 11,000-17,000 years ago. As a result, the ocean has absorbed enough carbon dioxide to lower its PH by 0.1 units, from 8.21 to 8.10 since the beginning of the industrial revolution which represents about 30% increase in acidity of the ocean. This is dangerous to aquatic ecological balance due to the biological effect of ocean acidification which interferes with marine life's ability to extract calcium from the water to build their shells and skeletons.

The energy sector is the largest contributor of global carbon dioxide emissions and second largest contributor of non-carbon dioxide greenhouse gas emissions globally. With electricity being the leading source of greenhouse gases, which are the cause of global warming, any effort to minimize greenhouse gases should address emissions from power generation. Sustainable grid electricity requires facilitating technologies and infrastructure like smart grids, decentralization of generation. A mixture of options is necessary to lower the unit cost and carbon intensity of energy systems to achieve a truly sustainable energy with low carbon world. Energy related GHG emissions are a result from conversion and delivery sectors like extraction/refining, power generation and direct transport of energy carriers in pipelines, cables, ships, tracks and end use sectors and industries like transport, buildings and construction, manufacturing, agriculture, forestry, households, and waste and hence cannot be blamed entirely on one sector or process alone.

21.4.13. Institutional Measures for the Transition

The sustainable transition strategies typically consist of three major technological changes namely, energy savings on the demand side, generation efficiency at production level and fossil fuel substitution by various renewable energy sources and low carbon nuclear. For the transition to remain technically and economically feasible and beneficial, policy initiatives are necessary to steer the global electricity transition towards a sustainable energy and electricity system.

Effective development of the green and sustainable energy sector requires international cooperation in research and development, policy development and administration, monitoring, and political cooperation. There is to put in place the legislative framework and financial measures that facilitate technological development for production of green and energy from renewable resources, while policymakers should create powerful tools for realization of sustainable development. It is important to place renewable and green energy systems at the center of sustainable development paradigm as a strategy to meet the international agreements and SGD 7 challenges.

The barriers that slow the growth of RGEs, including the following:

- i. Prohibitive cost of energy investment prices.
- ii. Weak energy infrastructure.
- iii. Legislative and policy challenges
- iv. Difficulties implementing environmental policies; and

- v. bureaucracy, among others.

It is through measures like:

- vi. Collaborative efforts between the public and private sectors that investment in renewable and green energy systems can be increased and realize a better environment, achieve energy security, and attain sustainable development.
- vii. Governments globally should put in place clear measures to increase the share of green and renewable sources to achieve sustainable development. The various strategies that can be utilized include.
- viii. Increase the level of responsibility and expectation to be placed on renewables in international agreements which seek to promote energy sustainability e.g., the Paris Agreement.
- ix. Governments should support energy movements within and without their borders through networking and collaboration.
- x. Increase the awareness of the importance of the renewable and green energy sources and role in attainment of sustainable development goals and
- xi. Enhance cooperation at the local, national, and international levels in critical areas of sustainable energy development like research and development, technology transfer, creation of new and cheaper technologies that can improve the exploitation of renewable and green sources of energy.
- xii. The use of subsidies can enable the deployment of clean energy resources by encouraging a shift from fossil fuel-based power generation into renewable-based power generation. Biomass and gas power may not be affected by subsidies. It is vital to focus on the subsidies for gas and biomass only when wind and solar generation technologies have matured. The carbon capture and storage (CCS) technologies will also play an important role in mitigating climate change and should be part of the energy transition strategy.

21.4.14. Greening the Power Sector

Many countries all over the world have taken measures to develop green energy from renewable sources, mainly solar power, hydropower, geothermal, wind, tidal wave, biogas, and biomass, to meet the growing energy demand. Sustainable development will be realised if states produce green energy in significant quantities. All net zero projects incorporate nuclear energy. Unfortunately, some countries like Belgium and Germany are gradually moving away from nuclear energy, although the ongoing energy crisis in Europe has

loosened the resolve to phase out nuclear power. The phase out will see higher use of natural gas in power generation particularly for Belgium and Germany. The same trend is projected for Taiwan and Canada where natural gas consumption will rise to fill the gap left by nuclear and coal phasedowns. For some development countries like Nigeria, Pakistan, and Philippines the share of fossil fuels in power generation has been growing and is projected to continue soon as their energy demand grows due to growth in their economies and populations. On the other hand, Kenya which is another fast-growing developing country is set to increase its share of renewables in the grid with increased geothermal power generation and phase-out of diesel power plants.

Many studies have shown that green energy is destined to be a part of the global future as a cleaner and more efficient solution to many of the current energy sources and applications. Green sources are easily renewed, have no harm to the environment, can create green jobs, and many are headed to become economically feasible as technologies advance. A fully sustainable future for global energy sources can be created without damaging the planet earth, by focusing on the development of a wide range of green energy alternatives. It is estimated that energy used for electricity and heat generation accounts for about 40% of global CO₂ emissions from fuel combustion, with coal plants supplying over 70% of this share. With fossil fuels accounting for about 43% of electricity mix in the G7 countries in 2022, more effort should be made to reduce to the targeted 32% by 2032. The situation was worse for China and India where fossil fuels accounted for 66% and 76% respectively of the electricity mix. Which is expected to drop to 53% and 67% respectively by 2032. More effort is therefore needed to green up the electricity grids in India and China.

Whereas nuclear, solar, geothermal and wind have significant potential to lead the transition, the power projects are highly capital intensive, while nuclear and geothermal have extremely long project delivery periods. Geothermal power development is also affected by development risks related to exploration and resource development which significantly affects their deployment in many developing countries. Public opinion continues to work against deployment of nuclear power generation projects. The higher cost of capital increases in several countries increases the risks of developing countries to continue using fossil fuels. Public support and investment is needed to enhance investment in capital intensive and risky nuclear and geothermal while deployment of technologies like modular reactors and wellhead technologies can fast track the deployment of nuclear and geothermal power plants.

Besides decarbonizing the power sector, adoption of green energy solutions in sectors like industry and transport as well as linking the energy and other sectors will create synergy that can help in faster deployment of green and renewable e.g., export cogeneration sector by the sugar industry and electrification of transport and industry operations with green power. Advances in the smart grid and development of the V2G and G2V will help to simultaneously decarbonize transport, industry and the electricity sector. Adoption of energy efficient technologies will also reduce energy consumption and related emissions in power sector and other related sectors like transport and industry.

Besides the technical and financial measures, the energy transition requires political goodwill to set up institutional, legal and policy measures to incentivize the transition. This will create a conducive environment that makes green and renewable energy systems attractive and competitive. They include attractive feed in tariffs and power purchase agreements, penalties for pollution and emissions.

21.4.15. Geothermal Energy and Use of Wellhead Power Plants in the Transition

Geothermal resources are significant globally especially in regions near the boundary of tectonic plates experiencing or have a history of volcanicity. Geothermal technology is also mature and readily accessible. However, geothermal challenges like long project development times with conventional power plants taking average of 5–10 years and with high risks associated with drilling and unproductive wells which discourage private investment and quick deployment. Geothermal power plants are reliable in grid electricity generation and operate at capacity factor of over 95%, making them ideal for baseload application. However geothermal electricity currently accounts for less than 1% of global electricity generation due to low growth in generation capacity of about 4.01% annually mainly due to huge capital requirements, high upfront development risks and long project delivery period of 5–10 years. By application of wellhead technology, the deployment of geothermal power will increase as they take 3 to 6 months instead of 5-10 years taken by the conventional power plants.

21.4.16. Waste plastics Recycling.

The use of plastics generates significant quantities of waste plastics currently contaminate the waterways, aquifers and limits the landfill areas. Over 14 million tons of plastics are annually dumped and as a result, they cause the death of 1,000,000 species of aquatic life. Plastic

pyrolysis is an attractive option for plastic waste as many authorities and countries globally call for a ban of several of plastic categories from the market due to failure by the conventional methods of plastic waste control to address environmental pollution by plastic wastes. The process however still faces several limitations particularly with respect to collection, separation, sorting and cleaning operations and high cost of power and transportation.

Pyrolysis generally produces fewer toxic products if the process is well designed, and process conditions controlled appropriately. However, the process has notable issues surrounding some toxic byproducts from plastics like polyvinyl chloride, which requires proper feedstock selection. Another challenge is that the liquid fuel from plastic pyrolysis is not a perfect fit for many engineered applications mainly because of relatively high Sulphur content which can be addressed though further treatment and blending with commercial grade oil products. Other than liquid pyrolysis oil, hydrocarbon rich gas is produced having heating value of 25–45 MJ/kg which makes it ideal for process energy recovery. Hence the pyrolysis gas can be fed back to the process to extract the energy for the process heating purpose which substantially reduces the reliance on external heating sources. A leading challenge in plastic recycling is the recycling of mixed plastics wastes. The main advantage is ability to recycle significant proportion waste stream through postconsumer collection of plastics to include wider variety of materials and pack types. More opportunities for recycling are being created by technological advances in technologies and systems applied for collection, sorting, and processing of used plastics aided by the combined effort of the public, environmental authorities, industry, and governments to ensure that majority of plastic waste are recycled.

20.4.17. The Energy Transition Challenges, Opportunities

The growing concerns over global warming highlight the importance of the global transition towards a “green economy” through less consumption of fossil fuel and emission of greenhouse gases. Energy transition refers to changes undertaken in fundamental processes in charge of evolution of human societies that drive and are driven by technical, economic, and social changes[1125]. It is a new path for economic development and innovation that does not compromise the environmental integrity and sustainability motivated by challenges caused by greenhouse gas emissions, climate change and natural resource depletion[1126]. The transition involves a shift from fossil-based global energy sectors dominated by oil, natural gas, and coal to renewable energy sources like solar, wind and low carbon sources like nuclear lithium-ion batteries[118]. An energy transition is a broad shift in technologies

and behaviors to enable the replacement of one source of energy with another. According to the transition is defined as the process of changing from one state or condition to another over a given time. This transition can occur in firms, cities, individuals, regions, and countries, and can be based on incremental or transformative change[1, 3].

Higher penetration of renewable energy into the energy mix, electrification and growth of energy storage are all key drivers of the energy transition. The energy transition will continue to increase in importance as priority is placed on environmental, social, economic, technical and governance factors in energy planning. The switch from fossil fuel sources will be enhanced by technological advancements and a societal push toward sustainability [2, 3, 61]. The transition to renewable energy includes a shift from internal combustion engine driven vehicles to electric vehicles, electrification of building heating, with heat pumps use of energy storage and smart grids for variable, weather-dependent technologies[119].

Therefore generating power from renewables, nuclear power, electrification of transport, mass deployment of energy storage, higher or improved energy efficiency will drive the transition with political goodwill and growing public support for lower greenhouse gas-emitting power generation and a clean energy economy [22, 23, 39].

The world has so far witnessed three typical energy transitions. The first transition involved replacement of wood with coal as the main energy source. In the second transition, oil replaced coal as the dominant energy resource. In the third transition, there is global commitment to replace fossil fuels with renewable energy. As in 2018, 80% of the global energy was derived from fossil fuel energy resources with 36% being petroleum, 13.2% for coal, and 31% was from natural gas[122]. Energy transition consists of processes of structural changes to the subsystems of society which lead to greater sustainability in the society[168]. Therefore energy transitions call for changes in existing policies, technology as well as supply and demand patterns for electricity and other energy resources[1126]. The world is said to be undergoing a fourth energy transition today having witnessed three energy transitions in the past. The main objective of this fourth transition is to fight the global climate change through decarbonization of the energy supply and consumption patterns[585]. Therefore a sustainable energy transition system must be driven by the climate change agenda, technology developments and innovation, increased energy efficiency, competitive economies, enhanced energy security, development of affordable energy solutions and measures and modernization of the energy sector from traditional energy systems[585, 1125]. The International Renewable Energy Agency (IRA) defines energy transition as the pathway

in the transformation of the global energy sector from fossil-dominated mix to zero-carbon by the second half of the 21st century[146].

The criteria for ranking and selection of energy sources and technologies for a sustainable energy transition should consider the environmental, technical, social, institutional, and economic dimensions of sustainability [132, 149]. Preferences should be given to renewable energy sources as global population and socio-economic activities increase leading to continuous urbanization and industrialization globally and hence more demand for natural energy resources [131]., whereas the world's population has increased by about 2.5 times since 1950, global energy demand has grown by about 7 times[135], with most of the demand being met by fossil fuels. These increasing energy demand is predominantly met by fossil fuel combustion and nuclear energy [150]. With ever increasing energy demand, the related challenges are depletion of fossil fuel reserves, their price volatility, and global climate change which have combined to make renewable and low carbon energy sources more attractive for power generation and thus many many countries have adopted policy, strategic and operational measures to promote low carbon options for the global energy transition [131].

20.4.17. Summary of findings from the study

- The cumulative effect of the Stockholm, Rio, and Johannesburg conferences made sustainable energy development (SED) a very important factor in sustainable development. Therefore, energy sustainability is an important factor in achieving the sustainable development goals.
- All electricity generation technologies emit greenhouse gases at some point in their life cycle and hence have a carbon footprint. Which should be considered.
- Fossil-fuelled generation has a high carbon footprint, with most emissions produced during power plant operation. “Carbon capture and storage” could reduce these significantly, though this is unproven at full scale.
- Nuclear and renewable generation generally have a low carbon footprint. Most emissions are caused indirectly, such as during the construction of the technology itself.
- Carbon footprints are sensitive to factors including the technology's adopted for a given energy resource. Therefore, an effective energy plan should include optimal mix of both energy sources and energy conversion systems with use of enabling technology, policy, and legal frameworks.

- A sustainable mix of energy sources, conversion technologies, energy and power system infrastructure in a facilitating environment is a prerequisite for sustainable electricity generation and supply and should therefore be the starting point for sustainable electricity generation and supply planning and execution.
- The Paris Agreement of 2015 sets targets to be realized to limit greenhouse gas emissions and related global warming with the objective of reducing greenhouse gas emissions and global average temperature rise to 2 °C and preferably 1.5 °C. With the energy sector accounting for most of the anthropogenic emissions, cutting down emissions in the power and transport sectors hold the key for the transition.
- The energy transition seeks to transform the world order with respect to development and environment and particularly the use of energy in its many forms with priority to electricity.
- Sustainable energy transition should incorporate the three dimensions of sustainable development of social, environment and economic in addition to technical and political/institutional dimension.
- A sustainable global electricity transition will entail increased use of renewable energy sources particularly wind and solar, nuclear energy as a low carbon energy source, electrification of transport and thermal processes in industry, bioenergy, and waste to energy conversion, shift from coal and petroleum to natural gas, hydrogen as a fuel with low carbon footprint, increased energy efficiency.
- This transition can only take place successfully through collaboration between players locally and international with effective facilitating policy framework, facilitating infrastructure and technology development and adaptation, use of smart grids and various modelling and optimization facilities in decision support.
- Smart energy systems led by the smart grid infrastructure are identified as critical for this transition.
- Decentralized generation is considered as a solution to the realization of a sustainable electrification program by promoting use of local resources and reducing distribution losses and costs.
- Off grid energy and power solutions led by the micro grids are considered as a critical component of the sustainable energy and electricity transition
- Geothermal energy can be used for heat and power generation. The main technologies for power generation are the dry steam, flash steam, and binary cycles. Combination technologies applies two or more basic conversion system e.g. flash steam and binary.

Geothermal power generation can also be broadly divided into conventional and wellhead power plants.

- Nuclear energy is divided into conventional nuclear power plants or modular reactor power plants, and fusion power plants or fission power plants based on the type of reactor and mode of energy generation respectively.
- Solar power can be produced through solar photovoltaic (PV) or concentrated thermal solar power plant (CSP).
- Hydropower is divided into hydro with storage, river flow and pumped hydro power plants which are also treated as storage technologies.
- Electric vehicles can be used sources of decentralized power generation and grid connected storage in addition to being variable loads connected to the grid via the V2G infrastructure.
- Ocean energy sources considered in this study are classified broadly into wave energy, tidal power, ocean thermal and ocean osmotic energy resources all of which are still under development.
- This study recommends energy planning and dispatch of power plants on the basis of their broad sustainability indicators unlike the traditional approach which is based on least cost power development plan (LCPDP)
- The main dimensions of sustainability in energy development and consumption are environmental, social, political, economic, and technical sustainability. Therefore, energy sustainability is best analyzed within the five dimensions of energy sustainability to give the assessment a wholistic view.
- Fuel cells promise to play a leading role in the energy transition as potential sources of base load electricity and prime mover for vehicles effectively coupling the hydrogen with transport and power generation. The solid oxide fuel cells have the highest average temperature followed by molten oxide fuel cells making them ideal for cogeneration. The alkaline and direct methanol fuel cells have the lowest average working temperature hence more ideal for domestic or household applications. High temperatures can support cogeneration hence an opportunity for more efficient energy systems.
- Hydrogen is a key energy resource for the energy transition, but with most of hydrogen today being produced by reforming natural gas and coal, there is need to increase production of green hydrogen from sources like electrolysis and development of hydrogen infrastructure, efficient and safe conversion systems like fuel cells.

- Promising energy sources like hydrogen fuel cells, biomethane and energy storage like pumped hydrogen face the challenge of low energy payback ratio and calls for process efficiency improvement and use of renewable energy sources for input energy to guarantee environmental sustainability.
- Bagasse has one of the lowest levelized cost of energy and electricity, low lifecycle emissions and higher energy payback periods making it one of the most sustainable energy sources for decentralised generation through bagasse cogeneration which is a mature technology. Through bagasse cogeneration, the sustainability of the sugar cane industry will be enhanced while grids will benefit from decentralised grid-based generation.
- Variable and intermittent sources of power and load like wind, solar, and electric vehicles have an important role in the energy transition supplying sustainable power and balancing loads for the grid. However, their full potential can only be achieved by the development of cost-effective grid scale storage, decentralisation of generation and a resilient grid provided by the smart grid infrastructure which calls for the transformation of the traditional grid to a smart grid.
- The use of modular power plants i.e. small modular reactors (SMRs) for nuclear and wellhead power plants for geothermal power generation provide pathways for faster and flexible development of power plants with long project gestation periods and those with high capacity and huge capital requirement like conventional geothermal and nuclear power plants.
- The sustainability of fossil fuel powerplants can be increased by conversion from coal and oil to cleaner natural gas, use of combined cycle generation for diesel and gas turbines and application of carbon capture and sequestration. This should however be a short to medium term options and should carefully be done to avoid compromising the transition by delaying or creating stranded assets during the net zero transition.
- Diesel power plant cogeneration and gas turbine combined cycle approaches can increase generation capacity by an average of 10% while reducing the energy payback ratio, specific fuel consumption, emissions density, and overall sustainability of the power systems.
- The Lifecycle approach to energy and power system planning provides a more realistic approach to sustainability planning by assessing the entire lifecycle of energy and power systems since some emissions and costs take place both upstream and downstream the value chain.

- Waste to energy sources of power have proven through their sustainability analysis to provide more sustainable energy and electricity on basis of lifecycle analysis e.g. energy payback ratio, lifecycle emissions and levelized cost of energy and electricity by providing a sustainable means of waste treatment and disposal thus making anaerobic digestion, plastic pyrolysis, and gasification important processes for the energy transition for production of biogas, biomethane, producer gas, syngas and pyrolysis oil that have significant energy value.
- Recovery of waste heat from geothermal used brine is an effective and efficient system to generate extra power from the flash cycle powerplants. Optimum recovery should involve careful selection of the working fluid and sizing of the expander and condenser with potential to generate as much as 15% extra power. Therefore, geothermal power developers should select more efficient cycles like binary cycles, carefully select the cycle equipment and speed up power deployment by use of wellhead generators during and if feasible after steam field development.
- Biomethane has similar properties with natural gas, hence will provide a sustainable substitute for all natural gas applications. However, biomethane productions should be improved to increase the energy payback ratio through more energy efficient processes.
- On lifecycle basis, coal power plants with no carbon capture proved to be the highest emitter of greenhouse gases with nuclear and wind having the least environmental impact.
- On lifecycle basis, bagasse cogeneration powerplants are the most economical.
- Nuclear, hydro power plants, geothermal, fuel cells, operate at high load and factor and are non-dispatchable sources making them ideal for baseload power supply. Ocean thermal, ocean osmotic and hydrodynamic power plants are also ideal for baseload due to their steady nature of energy supply.
- The dual cycle diesel engines, combined cycle gas turbines using natural gas, biomethane and hydrogen, as fuel are ideal for intermediate and peak power supply. Others are pumped hydro, grid scales storage,
- The power plants that will play an important role as non-dispatchable sources to be given way once available are solar, power plants, wind power plants, ocean wave energy, tidal power plants and electric vehicles (V2G). The maximum uptake of these variable sources of power will be significantly improved by the development of the smart grids and microgrids.

- The energy transition envisaged will only be possible if appropriate energy sources and power plants are supported by infrastructure, technology, concepts and policies like the smart grids and microgrids, decentralisation of generation, energy storage, energy markets with variable pricing and two-way communication, carbon capture and sequestration, demand side and behind the meter managing, facilitating legal and policy framework, smart energy modelling and optimisation tools.
- By application of demand side management and behind the meter measures supported by advances in smart grid capability of two-way flow of power and information, consumers will be converted to prosumers capable of supplying excess energy to the grid. This will be further enhanced by the energy market with variable pricing that can motivate consumers to sell to the grid when prices are favourable or consuming own power when prices are high in addition to application of storage for excess energy that is not demanded by the utility and the producer.
- Effective planning, deployment, and optimisation of energy resources and powerplants on long-term and real time basis will be enhanced by incorporating energy management tools and systems like HOMER, EnergyPLAN, guided by factors like the planning horizon, timescales, type of function e.g. energy planning or generation scheduling and number and complexity of objective functions.
- The transport sector can play a leading role in the energy transition by coupling it to the energy sector through electrification and use green electricity for the grid to power vehicles and reduce the transport sector derived greenhouse gas emissions by avoiding the use of fossil fuel sources.
- The V2X technologies like V2G technology and use of hybrid vehicles will enable the use of green and renewable fuels like hydrogen, biodiesel, bioethanol, biogas and biomethane, and natural gas as a cleaner fossil fuel can drive and charge vehicles for later supply power to the grid.
- Hydrogen and fuel cell technologies have the potential to enable the global energy transition as cleaner and more efficient in power generation since hydrogen is a renewable, and emission-free and can be produced using renewable energy sources like solar and wind
- Hydrogen faces the challenge of cost of production for green hydrogen while most hydrogen is derived from coal and natural gas which are non-renewable, it also has transport, safety and handling challenges to be addressed.
- Hydrogen is ideally used as an energy carrier rather than energy source due to high energy consumption and cost of production
- The internal combustion engine remains the dominant and traditional prime movers for the transport sector but have the lowest conversion efficiency of all feasible options for the energy transition making it technically attractive to shift to more efficient and cleaner options like fuel cells and electric traction.

CHAPTER 22:

CONCLUSSIONS AND RECOMMENDATIONS

22. Overview

This chapter presents the main conclusions based on the research objectives (ROs) addressed in this thesis and lays out the overall direction for future work.

22.1. Conclusions

Sustainable development cannot be achieved without sustainable energy which facilitates sustainable electricity generation. Whereas sustainable development can be analyzed within three dimensions representing the three pillars of sustainable development namely economic, social, and environmental dimensions, sustainable energy is best analyzed within five dimensions namely social, economic, environmental, institutional, or political, and technical. The sustainable transition strategies typically consist of three major technological changes namely, energy savings on the demand side, generation efficiency at production level and fossil fuel substitution by various renewable energy sources like biogas, biomethane, solar, wind and hydrogen and low carbon nuclear. For the transition to remain technically and economically feasible and beneficial, policy initiatives are necessary to steer the global electricity transformation from fossil fuel dominated towards a sustainable energy and electricity systems. Whereas renewable sources of energy hold the key for sustainable energy transition, large-scale renewable energy adoption should include measures to improve efficiency of existing nonrenewable sources which still have an important cost reduction and stabilization role. A resilient grid with advanced energy storage for storage and absorption of variable renewables should also be part of the transition strategies.

The world has so far witnessed three typical energy transitions. The first transition involved replacement of wood with coal as the main energy source. In the second transition, oil replaced coal as the dominant energy resource. In the third transition, there is global commitment to replace fossil fuels with renewable energy resources. Through the cumulative effect of the Stockholm, Rio, and Johannesburg conferences, sustainable energy development (SED) was identified as a key requirement for sustainable development and therefore energy was linked to the environmental dimension in the Stockholm conference, economy in the Rio conference and society in the Johannesburg conference. Sustainable development is expected to bring economic and social progress in an environmentally benign

manner free from wastage, pollution, destructive emissions and social strife in a facilitating political environment. Sustainable development has got three main dimensions of economic, social, and environmental aspects while sustainable energy has got two additional dimensions of technical and institutional or political environment which leads to five dimensions of energy sustainability analysis.

The concept of sustainability has received significant attention globally because of its multidisciplinary nature and interest in sustainable development. Sustainable development and sustainability mainly rely on the three basic pillars, namely economy, environment, and society. Sustainable energy systems should meet present demands by maintaining an adequate balance between economy, environment, and society, while remaining non depletable and thus ensure or guarantee future use. Energy sustainability assessment requires measurable indicators from the five dimensions of sustainable energy. Multicriteria decision analysis (MCDA) is a popular way for evaluating the sustainability of energy systems using well established models like EnergyPlan.

The greatest sustainability challenge facing humanity today is greenhouse gas emissions and the global climate change with fossil fuels led by coal, natural gas and oil contributing close to 61.3% of global electricity generation in the year 2023. Through sustainable energy, the dependence on fossil fuel sources is reduced while increasing the use of renewable sources of energy thus reducing greenhouse gases. Renewable energy technologies may be divided into three generations. The first generation commenced in the nineteenth century and relied on hydropower biomass and geothermal energy. The second generation started in the 1980s and consisted of consists of tidal, wind power, wave power, and solar energy. The third stage or generation is still under development today and is based on gasification, bio-refinery, and ocean thermal power. Electricity is the most dominant form of energy deriving its supply from both renewable and nonrenewable sources. The optimum operation of the grid electricity system is influenced by many dynamic variables which must be determined and controlled, managed, or accommodated to deliver reliable, affordable, and clean electricity. Sustainable grid electricity transformation needs competitive and cost-effective financing mechanisms to accelerate the transition, needs reliable energy supplies, and application of effective business and operation modelling tools that can deliver sustainable electricity which also needs new technology and data capability to analyze, and optimize results on real-time basis and in medium- and long-term planning.

Technology has a very important role to play in the transition to a low carbon electricity grid and economy. Technology options to facilitate the energy transition will include rapid digitalization of the energy sector which will enhance its flexibility and resilience to absorb variable renewable sources of energy particularly wind and solar. Important technology include transition from the traditional grid based on centralized generation to smart grids which support decentralized generation and ability to absorb the fluctuating renewable energy sources like solar and wind and fluctuating demand like electric cars while guaranteeing a stable and reliable electricity supply. By adopting or transforming the traditional grid to the smart grid and microgrids, the uptake of variable renewables like wind and solar can be increased from 20-25% of the grid connected power to 90-100% uptake. Decentralization of generation leading to enhanced use of variable renewables will further be enhanced by use of micro grid technology in remote areas far away from the public grid. Microgrids, facilitate balancing of generation from variable renewable power sources such as solar, wind, and hydro and conventional sources like gas-fueled combustion turbines, coal, and diesel power plants.

Since greenhouse gas emissions come from sectors like extraction/refining, power generation and direct transport, agriculture, industry, and homes, electrification of all industries and homes with power coming from renewable sources of energy will greatly succeed in cutting down global emissions. The broad strategies adopted for sustainable transition include liberalisation and restructuring of electricity and other energy markets which is made attractive by ever growing energy demand globally. Key policies adopted should aim at making electricity markets work better. More research and development into efficient, environmentally friendly, and competitive technologies is needed to facilitate innovation and diffusion of sustainable energy technologies. To realise successful implementation of the proposed policies calls for reduction in unit cost of electricity and ensure an affordable cost of appropriate energy carriers and services, and establishing regulations to increase efficiency and reduce energy related environmental for greater public benefits.

The implementation of effective sustainable energy technologies to minimize carbon emissions will require the use of renewable and low carbon sources of energy and adoption of three main strategies namely conventional mitigation, negative emissions technologies which capture and sequester carbon emissions and finally technologies which alter the global atmospheric radiative energy budget to stabilize and reduce global average temperature.

Besides low emissions, a sustainable electricity grid system should be stable and supply reliable, affordable, and socially acceptable electricity.

Although there is no consensus on quantitative factors and their magnitude, there is agreement on the need for supportive policies, regulations, programmes, and international commitments. Other measures are the development and expansion of financial sector, and improvement on the performance and quality of energy sector institutions. This study concludes that both renewable and non-renewable sources of energy have a leading role to play in the short and long-term energy transition. They include energy sources like solar, wind, hydro, hydrogen, bio resources, marine energy, nuclear, natural gas substitute of other fossil fuels and application of clean and efficient technologies for existing fossil fuel and non-renewable systems. Important strategies include electrification of thermal applications and household, and technologies like smart grids and energy storage for variable renewables and carbon capture and sequestration, cogeneration, and energy efficiency measures to limit consumption and wastage of energy resources. Waste to energy and particularly in form of electricity will minimize solid waste load and reduce environmental pollution like water and soil contamination. With the grid connecting different energy sources and infrastructure, decision support systems and optimization models will play a key role in realizing cost effective and environmentally friendly and reliable electricity generation and supply. Technology measures to control global warming can be classified into three broad categories of carbon capture and sequestration, emission mitigation strategies and technologies that alter the radiative properties of incoming and outgoing solar radiations.

Some energy sources and power plants like nuclear and geothermal require significant capital investment and long project delivery periods of 5 to 10 years on average. The solution to these challenges is the use of modular wellhead generators which take on average 3-6 months to deliver power by installing the generators. For nuclear power which faces similar challenges, development of (Small modular reactors) SMR increases flexibility in development and deployment of small reactors for small scale applications and phased deployment. This reduces risks and capital requirements making it possible to apply nuclear and geothermal power decentralized generation and thus play a critical role in the unfolding global energy transition.

Therefore, measures related to emissions needed for the transition are those that use conventional mitigation, negative emissions technologies which capture and sequester carbon emissions and finally technologies which alter the global atmospheric radiative energy budget to stabilize and reduce global average temperature. Although fossil fuel sources are the main

cause of energy related emissions, complete substitution with renewable sources may not be possible in the short and medium term and will therefore continue to play a critical role in future sustainable power systems as dispatchable source of power for the grid. However, their sustainability should be enhanced by limiting their use to peak and emergency applications and application of more efficient technologies and approaches like cogeneration and combined power systems in fossil fuel power plants like, use of less polluting natural gas which can later be substituted by biogas and biomethane in power generation and transport sector while direct carbon capture and sequestration should be applied to minimise emissions produced and released to the environment. Since most emissions are concentrated at generation point, application of carbon capture, storage, and sequestration before their eventual elimination from the energy mix can contribute to the transition. As stop gap measure, natural gas which stands out as the cleanest fossil fuel can be used to replace more polluting coal and diesel power plants in power plants as well as kerosene and other fossil fuels in gas turbine power plants could reduce these significantly, Therefore, an optimised mix of both renewable and non-renewable sources of energy will form critical component of the future sustainable energy and power systems but application of requisite technology is necessary for both long term planning, and real time dispatch of the power plants and energy sources.

Nuclear energy and power plants have relatively low carbon footprint and the available uranium reserves and other radioactive materials for nuclear power generation are significant globally. As a low carbon resource, nuclear will play a leading role in the energy transition for direct power generation and coupling with the hydrogen sector for use in the manufacture of renewable hydrogen energy which has huge potential in the future sustainable energy systems with feasible applications in power generation through fossil fuels, manufacture of industrial and transport fuels and powering the transport sector and many other applications as a renewable energy carrier. Hydrogen will also substitute fossil fuels in direct combustion applications in power plants like diesel and gas turbines power plants, but technological progress is required for the prime movers to use hydrogen. With most hydrogen being produced from fossil fuels; production of green hydrogen is the key for the sustainable energy transition.

. Hydrogen energy can be classified as renewable based on source of hydrogen gas, and is emission-free fuel if produced using renewable energy sources like solar and wind. The study demonstrated that hydrogen and fuel cell technologies have significant potential to as low-carbon energy resource and power sources respectively mainly because hydrogen has

hydrogen can act as both an energy resource and energy carrier with high calorific value while fuel cells operate at a high average capacity factor of 50-70% and reliability of up to 99% but with the main challenge being over 90% of hydrogen produced globally is from fossil fuel sources hence nonrenewable and just about 1% being classified as green hydrogen mainly from electrolysis in which energy needed to produce renewable hydrogen is more than the energy in hydrogen making hydrogen ideal as an energy carrier rather than an energy source.

The internal combustion engines remain the traditional prime movers for the transport sector having average conversion efficiency 12.7%, compared with pure electric vehicles with average conversion efficiency of 51.6% while fuel cells as prime movers have an average efficiency of 28.3%. The hydrogen ICE (HICE) vehicles have about 26.6% conversion efficiency. This makes the internal combustion engines the least efficient of the feasible prime movers for the transport sector. This is an opportunity for replacing the internal combustion engines with more efficient and renewable sources like fuel cells, electric vehicles and hydrogen powered internal combustion engines for the energy transition.

The transport sector remains challenging within the framework of transition to 100% renewable energy system, the transport sector remains one of the most challenging since it is difficult to electrify all operations like heavy duty transport, shipping and air travel will which will continue to rely partially on or fully on liquid or gaseous fuels due to the fluctuating nature of important renewables and the dynamic nature of electricity demand. A combination of electrification and use of renewable fuels like biomethane and green hydrogen will be key options in the transition for the energy sector. This research that transition to 100% renewable sources cannot be achieved suddenly, instead it will be gradually realised with continued contribution of fossil fuels and nuclear energy, but in a diminishing contribution within the year 2050 target set by the global community through gradual but sustained substitutions. Therefore power generation from renewable sources like wind, solar, biomethane, bagasse and green hydrogen, generation from low carbon nuclear, energy, electrification of transport, industrial and domestic operations and processes, mass deployment of energy storage, higher energy use and power generation efficiency, adoption of enabling technologies and concepts like smartgrids, microgrids and decentralized generation are the main measures that will drive the global energy transition with political goodwill and growing public support for lower greenhouse gas-emitting power generation and a clean energy economy

21.2.Recommendations

The energy sector is an essential component of social and economic development because of the link between economic activity at levels of energy consumption. On a global scale, we have a positive correlation between per capita income and per capita energy use. The use of renewable green energy provides an attractive alternative for socio-economic development, job creation, reduced emissions, and realization of the sustainable development goals (SDGs). Communities that can produce, share, sale, and store renewable and sustainable energy green energy have a leading role to play in the development of a decentralized, digitalized, and decarbonized power system. However, to realize this needs significant collaboration between various stake holders and enabling technologies like smart grids, microgrids, decentralization of generation, and demand side energy management infrastructure.

This study lays the foundation for further research into technical and non-technical measures to ensure a sustainable transition to a low carbon electricity grid from different sources, both renewable and nonrenewable and forms a firm foundation for effective policy formulation and implementation necessary to drive the energy transition globally. Further research into practical details of the technologies and measures is recommended to guide the actual implementation of the transition measures and strategies like smart grids, decentralized generation, energy storage, decentralized generation and computerization and optimization of electricity generation, transmission, and distribution resources to facilitate a sustainable energy future. The study further recommends identification and development of transition specific energy and electricity models to aid in planning and execution of sustainable energy and electricity production, supply and consumption by end users, utilities, and prosumers.

21.2.1. Policy Recommendations from the study

It was demonstrated by this study that both renewable and non-renewable sources of energy have an important role to play in the sustainable energy future with low carbon nuclear energy and renewable energy sources holding the key to the energy transition. Developing countries can ‘leapfrog’ fossil fuels, by avoiding going down the path taken by most developed countries by limiting dependence on fossil fuels, especially coal and oil. Through greater use of renewable energy sources while relegating the use of gas for peripheral role of stabilising the electricity grids. Through decentralisation of power systems, nations can achieve accelerated energy transition. This however does not imply that a country can leapfrog to 100 per cent renewable energy grids with many models proposing carbon neutrality by 2050, For rapid growth in power generation for economic development of developing countries, there is need to invest investments in a mix of generation technologies

in the middle term with measures to increase uptake of renewable energy electricity by the grids. The specific policy recommendations include.

- i.) Authorities should put in place rules and regulations that seek to motivate adoption of clean energy sources and technologies e.g. carbon taxes on fossil fuels, tax reliefs and exemptions for green investments.
- ii.) The power purchase agreements for renewable and variable sources should not be punitive for failure to deliver power. The agreements should be based on real challenges facing prosumers like the case of Mumias Sugar Company Ltd. which eventually went into receivership partly due to a punitive power purchase agreement for cogenerated electricity supplied to the national grid.
- iii.) Governments and power utilities should put in place attractive feed in tariffs for green electricity to compete favourably with conventional electricity from fossil fuel sources.
- iv.) International, national, and regional institutions should be developed to promote collaborations that will create synergy and institutionalise the development of new technologies and energy sources for the transition for promising sources and technologies like biogas and biomethane, hydrogen and fuel cells, ocean energy sources and energy conversion technologies, wind and solar. This will contribute to sustainable energy transition through the institutional and political dimension through measures like standardization, collaboration, and technology transfer.
- v.) Since technology holds the key for the energy transition, governments should fund domestic and international research and development of new and appropriate energy technology development and transfer.
- vi.) The financial dimension is a very important dimension of the sustainable energy transition. Global and local financial mechanisms and products should be put in place to avail the huge financial resources needed to develop sustainable energy transitions.
- vii.) Decentralisation of generation is the best way to utilise renewable and sustainable energy resources most of which are renewable like wind and solar which also face the challenges of variability and intermittence with can be best addressed by the development of the smart grids and microgrids. Therefore, transforming the traditional one-way grid to a two-way resilient and intelligent smart grid is key to the energy transition and realisation of the global emissions and climate targets set

in the Paris Agreement. The huge costs and technologies required call political support and international collaboration and funding.

- viii.) Variable pricing and efficient energy markets should be put in place by governments and utilities as well as application of tools like demand side management and behind the meter management strategies to convert consumers into prosumers who can profit from the excess energy resources at their disposal. This will significantly aid the energy transition and help achieve the global climate and emissions targets centered around local sustainable energy resources through decentralised generation.
- ix.) Lifecycle assessment should be used to establish the real environmental impact of energy sources and power plants by considering the carbon footprint due to operational emissions, upstream and downstream activities related emissions.
- x.) Countries and utilities should shift to the sustainability assessment based five-dimensional assessment in long term deployment and real time dispatch of energy and power systems to ensure a sustainable energy transition as opposed to narrow objective least cost energy planning (LCEP) applied by many utilities and governments globally in their energy and power planning. This will give all energy sources a positive consideration in the assessment based on their strengths, weaknesses and unique characteristics viewed both locally and globally in terms of value and potential contribution to society and energy & power systems.

21.2.2.Recommendations for future research

This study has demonstrated that both renewable and non-renewable sources of energy have an important role to play in the energy mix for a sustainable energy future. Low carbon nuclear energy and renewable energy sources hold the key to the energy transition. Developing countries can ‘leapfrog’ fossil fuels, by avoiding going down the path taken by most developed countries by limiting dependence on fossil fuels, especially coal and oil. Through greater use of renewable energy sources while relegating the use of gas for peripheral role of stabilising the electricity grids. Through decentralisation of power systems, nations can achieve accelerated energy transition. However, this does not imply that a country can leapfrog to 100 per cent renewable energy grids with many models proposing carbon neutrality by 2050. For rapid growth in power generation for economic development of developing countries, there is a need to develop a mix of generation technologies in the middle term with measures to increase uptake of renewable energy electricity by the grids.

This thesis focused on developing the scalable methodology suitable for large-scale long-range planning of electricity and real time management of generation facilities for optimum grid electricity generation which can help countries realize various energy and emission targets and obligations. To improve the applicability of the proposed methodology into standard practice, we need to resolve the following issues.

- i.) Further research into practical details of the technologies and measures is recommended to guide the actual implementation of the transition measures and strategies like smart grids, decentralized generation, energy storage, decentralized generation and computerization and optimization of electricity generation, transmission, and distribution resources to facilitate a sustainable energy future.
- ii.) The study further recommends identification and development of transition specific energy and electricity models to aid in planning and execution of sustainable energy and electricity production, supply and consumption by end users, utilities, and prosumers.

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