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# Development of Integrated Model and Framework for Sustainable Energy Resources and Systems Planning

Joseph Samuel Akpan

Supervisor
Prof. Olanrewaju Akanni Oludolapo

Head, Industrial Engineering
Prof. Olanrewaju Akanni Oludolapo
Durban University of Technology

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# Development of Integrated Model and Framework for Sustainable Energy Resources and Systems Planning

Joseph Samuel Akpan

(Student No: 22176142)

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Joseph Akpan

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# Declaration

I declare that:

(1) The content of this Thesis represents my work and opinion. Due acknowledgement has been given in the references to all sources of information - printed, electronic, or personal, as may be applicable.

(2) No portion of this thesis has been submitted in support of any application for any other degree or qualification of this or any other university or other institutes of learning.

[redacted]

Joseph Akpan
Student ID: 22176142

Date: …………………………..
***20/02/2024***

[redacted]

Prof. Olanrewaju Akanni Oludolapo
Supervisor

Date: …………………………..
**20/02/2024**

# Dedication

This thesis is dedicated to my family and my beloved mother and friend, who went to be with GOD during my master's study. Mum, I really missed you and hope to see you again when the time is ripe. Thank you so much for your self-less love and for showing us CHRIST.

# Acknowledgements

So far, my studies and research have been a wonderful journey. I am very thankful to the Almighty GOD, who has always been there for me and helped me. In addition to the people He brought into my life who made this journey achievable, I am grateful to him. For that reason, I want to express my deepest thanks to the following individuals and groups.

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- To my family (father, siblings, in-laws, nieces, and nephews) and my best friend – Idongesit Charis, your help and support remain a blissful memory for me. For all the love, care, patience, and belief in my ambitions and pursuits, thank you!

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# Abstract

Sustainable energy development (SED) is a crucial component of the Sustainable Development Goals (SDG), aiming to maintain economic and social progress while protecting the environment and mitigating climate change's effects. SED serves as a transition paradigm for sustainable development, providing a blueprint for energy peace and prosperity for people and all uses. The first objective of this dissertation is to identify 10 interlinked themes of SED and explore 2 of them, which are the least studied in existing SED reviews. These two themes include energy financing and commitment to climate change and the need for 100% renewable energy (RE), a part of the decarbonization strategy towards the 1.5 - 2.0 °C Scenario. The study suggests that the current G20 countries' contributions, if done continuously per annum, in addition to 80% more funding from private investment of the same amount in the 1.5°C scenario financial requirement for clean energy, is sufficient to limit global warming. In addition to the present drive for 100% RE for all purposes, an emphasis is placed on addressing other issues, such as energy storage options, developing countries' development agenda, and regional security stability to prevent energy wars. Emerging SED decarbonization strategies are presented across power, transport, building, and industrial sectors. This part concludes with a summary of SED progress and directions for future research, mainly the need for re-defining Nationally Determined Contribution (NDC) through a centralized global or regional stock-taking strategy for greenhouse gas emissions reduction.

Consequently, the next study attempts to address the limitations of the current NDC by formulating a policy hypothesis and applying it to an integrated assessment tool (here, termed the environmental model) for strategic stock-taking in reducing GHG emissions. In developing this indexing model, being the first objective of this thesis, we analysed the potential impact of Nationally Determined Contributions (NDCs) under the Paris Agreement on global temperature rise used as the key model input parameters with countries' historical data and other parameters such as GDP, population growth. With the use of an integrated assessment tool based on the concept of system dynamics, the analysis constructs a framework to project global temperature changes under five policy scenarios, namely baseline, current (announced energy policies 1 and 2), and optimum (2.0 $^0$C Scenario), and most optimum (1.5 $^0$C) case scenarios. The hypothesis is formulated based on the analysis of current, announced, and best-case global and or applicable national policy scenarios. The model aims to address critical questions regarding the effectiveness of the on-going NDCs commitments in limiting global temperature rise to well below 2$^0$C, in alignment with the Paris Agreement's goals. The simulation results offer a roadmap for optimizing the current NDCs in global and national energy policies and treaties, fostering international collaboration, and reinforcing the global commitment to combating climate change.

Leveraging on the preceding simulation result of the environmental model, a novel emissions budgeting (EB) model tool (here, termed the economic model) was introduced as a simplified approach for the determination of the economic attractiveness of the policy scenarios of the environmental model. Hence, the second objective, which was to determine the economic benefit of policy scenarios, was achieved.

Some advanced countries' rapid population, economic growth, and energy consumption from mostly 100% electricity that is majorly fossil-based contributes significantly to global $CO_2$ emissions. In contrast, the case in most developing countries is different. For instance, electricity access in Africa is less than 60%. Hence, this presents challenges and opportunities for achieving the United Nations' Sustainable Development Goals (SDGs) 7 and 13 of generating all energy from cleaner or low-carbon sources to reduce $CO_2$ emissions in all countries and combating climate change consequences. Therefore,

considering the peculiar situation of other developmental goals, such as increasing population access to electricity while being obliged with the need to transit to complete renewable energy, as our third objective, we explored the idea and transition paradigm of reaching a 100% renewable energy that is void of unjust energy transitioning, climate injustice, and unbiased drive for increasing renewables energy penetration in the global energy mix.

The increasing need for renewable energies has been widely acknowledged to greatly advance the climate change agenda as increasing clean energy usage depletes the accumulation of GHG in the atmosphere. Alongside reducing the accumulation of GHG, increasing RE share in the national mix has constantly become the core of many countries' energy policies and the agenda of many of the NDCs reported by countries. Presently, about 30 countries already with over 70% of their national electricity mix from RE. A part of this has birthed a new paradigm and an emerging field of 100% RE for all purposes, recently receiving much attention from academia and in public discourse.

Upon establishing the need for analysing the transition towards 100% RE, the thesis demonstrated this conceptual idea through a model (here, termed the energy model) to analyse the possibilities for a 100% renewable energy system at the global level. Because several studies have already done such analysis, however, this has hardly been directly linked to the climate scenarios. Therefore, this thesis bridged this gap in the literature by synthesising the energy transition at different percentage shares in the global primary energy mix over time with the effect on global temperature levels. The rationale behind this was to present a discussion on the pathway possibilities and challenges of achieving 100% RE and whether it is possible to meet the total global energy demand through RE, with what effect on the climate scenarios. To do this analysis, we further define our hypothesis using baseline, optimum, more optimum, and extreme optimum path scenarios to ascertain such possibilities. Finally, we used an integrated assessment model based on the principles of system dynamics to analyse these hypotheses and to find the implications of each action or scenario on other factors such as global temperature, GHG emissions, energy storage breakthrough while keeping the population growth at maximum possible value of 12.4 billion persons by 2100 with GDP growth rate not less than 1.5%. The findings are valuable in helping us discuss if 100% RE can be a reality and what the implications are. Our results show that in the baseline current scenarios, the global average temperature will most likely be kept at 3.3 $^0$C. Hence, the world would need very urgent and unprecedented efforts beyond the current baseline of business as usual.

Interestingly, our findings also indicate that to stay within the 1.5 and 2.0 $^0$C Scenarios, the world may need just between (58.6 - 77.3) % and (62.7 - 82.8) %, respectively, in the global energy mix. For the most optimistic scenario, (75.5 - 99.8) % RE may be required, and this is able to keep the temperature rise even well below 1.5 $^0$C but at 1.1 $^0$C. The 1.1 $^0$C possibility is quite highly ambitious, in my opinion, because it requires the intensity of global mix energy generation of about 6627 extra joules from renewables only.

The major challenge with the idea of 100% RE for all purposes is that achieving such a feat requires a more diverse approach and scarcely are there 100% RE studies that incorporate holistically the interrelation of several pertinent strategies. Therefore, there exists a need to meet both the technical and non-technical requirements. In order to address this shortcoming, our third objective introduces six methodological or evaluation mechanisms (herein, identified as 100% RE evaluation metrics) suitable for existing and future 100% renewable energy analysis. It then reviews energy modelling tools to identify their applicability to 100% RE analysis. The perspectives presented in this thesis are valuable in developing a common integrated methodology and modelling tool for analysing full renewable energy adoption in countries or regions with best trade-offs, using performance indices that have not been previously used. The proposed metrics could also help with proper national and regional energy resources and system planning for new energy projects and installations, contributing to sustainable development.

The framework and narrative, presented in the form of a model within this dissertation, make a noteworthy contribution to the ongoing discourse surrounding the energy transition as, to the best of my knowledge, this concept has not been presented this way. The results from this dissertation can be further investigated through a streamlined application of the approach at individual country or regional level to facilitate inclusive and climate-responsive planning and execution strategies for sustainable energy and electricity generation, distribution, and utilization at both national and urban levels. The implications of the findings have the potential to inform the United Nations Framework on Climate Change Convention (UNFCCC) and Conference of Parties (COP) policies in better ways of promoting equitable support for countries, regions, energy consumers, utilities, and prosumers.

# Graphical Abstract

# Development of integrated model and framework for sustainable energy resources & systems planning

## Introduction

- The study uses a critical discourse analysis to explore sustainable energy development (SED), identifying ten interconnected themes, with two most related to climate change scenarios of the Intergovernmental Panel on Climate Change, IPCC .
- The two most related SED themes are energy financing for towards the 1.5°C climate scenario and the upsurge for 100% renewable energy for all purposes .
- Three models (environment-ENV, economic-ECO, and energy-ENE) are introduced to examine these two themes of SED.
- The ENV model formulate and simulates alternative emissions reduction policies, while the ECO model evaluates the economic attractiveness of each policies. The ENE model assesses the feasibility of 100% renewable energy systems in the context of global temperature rise scenarios of the ENV and ECO models towards a more sustainable energy future.

## Research Approach

Two key approaches

1. Confirmatory Approach → ENV & ECO model
2. Exploratory Approach → ENE model

The integrated modelling were used based on principles of system dynamic modelling and capital budgeting techniques

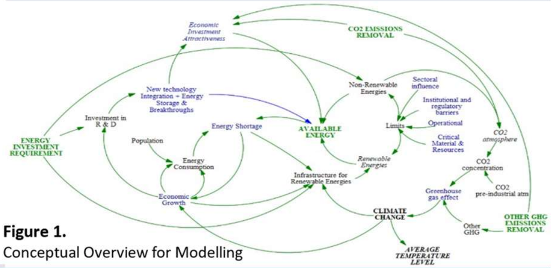

**Figure 1.**
Conceptual Overview for Modelling

## Results

### ENV Model Findings

1. The simulation results of the emissions reduction scenarios of Figures 1 provide insights into how the five scenarios might influence future temperature levels.
2. The percentage changes within a short time series appear very little compared with the case of the long-term difference, even with the large emission reduction commitments.
3. In the IPPC desired scenarios (i.e., 1.5$^o$C and 2.0$^o$C Scenarios), results shows that the world needs to increase its current annual National Determined Contribution (NDC) emissions reduction by about 6.5% (2.6Gtons $CO_2$ eq) and 2.5% (11.08Gtons $CO_2$ eq.) across all the regions, respectively.

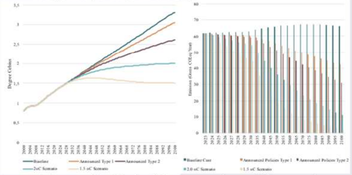

**Figure 3.** Global Temperature Rise and Emissions per policies (2023 - 2100)

### Integrated Model

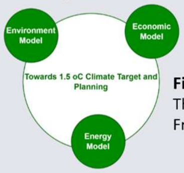

**Figure 2.** Theoretical Framework

### ECO Model Findings

1. The technical feasibility of reaching 1.5$^o$C climate goals is believed to be possible, but the challenge lies in the financial requirements.
2. An emissions cost-benefit budgeting model was developed to determine the attractiveness of each policies from the ENV model.

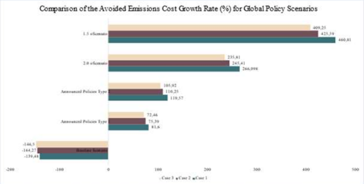

**Figure 4.** Avoided Emissions Growth Rate versus Policies

### ENE Model Findings

The ENE studied transition into 100% RE and the effect on global temperature levels $\mathbf{T_E}$ using sectoral contributions, population, and economic growths.

$$T_E = f\,(E_S,\ T_{ee},\ B_{ee}, I_{ee},\ G_{p,GDP}, LFI_e,\ C_r)$$

1. $E_S$ is energy supply from all the energy sources (Renewables, Oil, Coal, Natural gas, Nuclear, and Bioenergy).
2. $T_{ee}$, $B_{ee}$, $I_{ee}$ are electrification and energy efficiency for transport, building, and industry sectors.
3. $G_{p,GDP}$ growth in population and GDP
4. $LFI_e$ is the land, food, and industry emissions, while $C_r$ is the $CO_2$ removal rate.

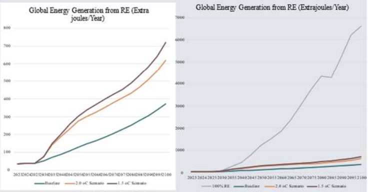

**Figure 5.** Global Energy Production versus Policies (2023 - 2100)

## Discussion

Considering these dynamics of cross-sectoral interactions and the interrelation between the SED themes as first reported [1], this study explored timely strategies towards the 1.5$^o$C Scenario. A simplified energy-climate model was developed using an integrated assessment approach to evaluate and manage multiple energy potentials, resources, and systems while creating a link between emissions reduction & energy policies for sustainable development goal 7 (clean and affordable energy for all), with the goal 13 (climate change action).

All the models showed that the 1.5$^o$C climate scenario were possible, but at a very ambitious emissions rates, yet with the highest net present value based on avoided emission rate growth. The ENV result model results shows that 100% RE may be possible by 2100 helping keep the temperature rise even by 1.1$^o$C. However, energy production from RE would have to be greater than 6000 extra joules/year.

## Research Contribution & Prospects

The ENV model focuses on fair transition to assess the equitable contributions of the categorized country and regions towards achieving the 1.5°C climate scenario, while the ECO model presents the attractiveness of the scenarios, and the ENE model presents a perspective on energy production requirement across the IPCC scenarios, & the 100% RE scenario. The models in this study can be linked to pre-existing integrated assessment models (IAMs).

## References

List of Research Outputs

# List of Research Outputs

## Journals

1. **Akpan Joseph**, and Olanrewaju Oludolapo. 2023. "Towards a Common Methodology and Modelling Tool for 100% Renewable Energy Analysis: A Review". Energies 16, no. 18 (September 2023): 1 - 42. https://doi.org/10.3390/en16186598 *(Selected as the Journal's Feature Paper based on recommendation by the scientific editors and positive feedback from the reviewers)*.

2. **Akpan Joseph**, and Olanrewaju Oludolapo. 2023. "Sustainable Energy Development: History and Recent Advances". Energies 16, no. 20 (October 2023): 1 - 44. https://doi.org/10.3390/en16207049 *(Selected as the Journal's Feature Paper based on recommendation by the scientific editors and positive feedback from the reviewers)*.

3. **Akpan Joseph**, and Olanrewaju Oludolapo. 2024. " A Novel Evaluation Approach for Emissions Mitigation Budgets & Planning Towards 1.5ºC and Alternative Scenarios". Atmosphere 15, no. 2 (February 2024): 1 – 36. https://doi.org/10.3390/atmos15020227

4. **Akpan Joseph**, and Olanrewaju Oludolapo. "A perspective analysis on the transition to 100% renewable energy versus the global temperature scenarios using EN-ROADS Model". (submitted)

## Book Chapters

1. **Akpan Joseph**, and Olanrewaju Oludolapo. 2023. "Towards the 1.5ºC Climate Scenario - Global Emissions Reduction Commitment Simulation and the Way Forward" Global Warming - A Concerning Component of Climate Change. IntechOpen. https://doi.org/10.5772/intechopen.1003851

2. **Akpan Joseph**, Olanrewaju Oludolapo, and Rubén Irusta. 2024. "A State-of-the-Art Approach for Assessing the Environmental Sustainability of Multi-Renewable Energy Systems in the Built Environment." Advances in Clean Energy Systems and Technologies, Green Energy and Technology, Springer Nature. https://doi.org/10.1007/978-3-031-49787-2_31

3. Kabeyi Moses, Olanrewaju Oludolapo, and **Akpan Joseph**. 2024. "Biogas Production and Process Control Improvements". From Biomass to Biobased Products. IntechOpen. https://doi.org/10.5772/intechopen.113061

## Conferences and Proceedings

1. Hagreaves Kumba, **Akpan Joseph**, Belinda Twite, and Oludolapo Olanrewaju. "Renewable Energy Adoption and Integration in South Africa: an overview". Paper presented at the 12th International Conference on Clean and Green Energy (ICCGE 2023), Xiamen, China. https://doi.org/10.1049/icp.2023.1607 (IET library and IEEE Xplore).

5. **Akpan Joseph**, and Olanrewaju Oludolapo. "Towards a Simplified and Integrated Model for Energy-Climate Resources and Systems Planning". Paper for the 12th International Conference on Smart Energy Grid Engineering (SEGE 2024), Ontario, Canada. (IEEE Xplore). (submitted)

## Poster

**Akpan Joseph**, and Olanrewaju Oludolapo. Towards a Simplified and Integrated Model for Energy-Climate Resources and Systems Planning. Poster presented at the 4th IEEE UK&I Young Professionals Postgraduate STEM Research Symposium, Northumbria University, Newcastle upon Tyne, United Kingdom, 2023. https://www.ieee-ukandireland.org/call-for-papers-4th-ieee-uki-young-professionals-postgraduate-stem-research-symposium.

# List of Awards and Honors

| | |
|---|---|
| University Platinum Prize for Top Master's Student (DUT) | 2023 |
| Masters' Student Research Recognition Award (Industrial Engineering Department, DUT) | 2022 |
| Erasmus+ KA107 Mobility and Traineeship Grants in Spain (European Union EU Commissions) | 2022, 2023 |
| Best Paper Award (IEEE 13th ICMIMT, Cape Town, South Africa) | 2022 |
| Best Graduate Student Paper Award-3rd position (5th IEOM EU Conference, Rome, Italy) | 2022 |
| DUT Postgraduate Scholarship | 2022, 2023 |

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# Abbreviations

| | |
|---|---|
| AI | Artificial intelligence |
| AP | Announced Pledges |
| ARR | Accounting Rate of Return |
| ASEAN | Association of Southeast Asian Nations |
| BP | Baseline path |
| BAU | Business-as-usual |
| BI | Budgeting Indices |
| CBA | Cost Benefit Analysis |
| CBI | Cost Benefit Index |
| CBT | Capital budgeting techniques |
| CC | Clean conditional |
| CCS | Carbon capture strategies |
| CCIP | Climate-change impact potential |
| CDM | Clean Development Mechanism |
| CES | Chemical energy storage |
| CER | Certified Emission Reduction |
| CU | Clean unconditional |
| CNG | Compressed natural gas |
| COP | Conference of Parties |
| CSD-9 | Commission on Sustainable Development |
| CSP | Corporate sustainability performance |
| DCF | Discounted cash flow |
| EB | Emissions budgeting |
| ECO | Economic |
| EEED | Energy–Economy–Environment and Development |
| EESG | Economy for Sustainable Growth |
| EEI | Economic, environmental, and social impacts |
| EMT | Energy modeling tools |
| ENE | Energy |
| ENU | Energy Use |
| ENV | Environment |
| EOP | Extreme Optimistic path |
| EROI | Energy return on investment |
| ETP | Energy Transition Plan |
| ESG | Environmental, social, and governance |
| EEA | European Environment Agency |
| ESA | Energy System Analysis |
| EU | European Union |
| EV | Electric vehicle |
| eZEC | Effective zero emissions commitment |
| FC | Fossil conditional |
| FCB | Fair carbon budget share |
| FEC | Freshwater Ecotoxicity |
| FEP | Freshwater Eutrophication |
| FFF | Fridays for Future movement |
| FiT | Feed-in tariffs |
| FU | Fossil unconditional |
| GCC | Gulf Cooperation Council |
| GCB | Global Carbon Budget |
| GDC | Globally Determined Commitment |
| GDP | Gross Domestic Product |
| GEF | Green energy finance |
| GEI | Green energy technology/innovation |
| GHG | Greenhouse gas |
| GW | GigaWatt |
| GWP | Global warming potential |
| HC | Hosting Capacity |
| HFCs | Hydrofluorocarbons |
| HTc | Human Toxicity, Cancer Effects |
| HTnc | Human Toxicity, Non-cancer Effects |
| IAM | Integrated Assessment modeling |
| INDC | Intended nationally determined contribution |
| IPCC | Intergovernmental Panel on Climate Change |
| IAEA | International Atomic Energy Agency |
| IEA | International Energy Agency |
| IPG | International Partner Group |
| IRENA | International Renewable Energy Agency |
| IRHH | Ionising Radiation Human Health Effect |
| IRR | Internal Rate of Return |
| JETIP | Just Energy Transition Investment Plan |
| KerCA | Kernel-based comprehensive assessment |
| LCOE | Levelized Cost of Energy |
| LCOES | Levelized Cost of Energy Storage |
| LU | Land Use |
| MAC | Marginal Abatement Cost of Emissions |
| MEP | Marine Eutrophication |
| MFRD | Mineral, Fossil and Renewables Resource Depletion |

| | |
|---|---|
| MCDM | Multi-criterion decision-making |
| ML | Machine learning |
| MOP | More optimistic path |
| MTCO2eq | Metric ton of $CO_2$ equivalent |
| NDC | Nationally Determined Contribution |
| NPV | Net Present Value |
| NZE | Net Zero |
| OECD | Organization for Economic Co-operation and Development |
| ODP | Ozone depletion |
| OP | Optimistic path |
| OT | Other energy type |
| PA | Paris Agreement |
| PBP | Pay Back Period |
| PCC | Point of common coupling |
| PCF | Pan-Canadian Framework on Clean Growth and Climate Change |
| PFC | Perfluorocarbon |
| PI | Profitability Index |
| PLI | Production-Linked Incentive |
| PM | Particulate Matter |
| POF | Photochemical Ozone Formation |
| PPPs | Purchasing Power Parities |
| PRA | Policy and regulatory analysis |
| PV | Photovoltaic |
| RAC | Rest of the Advanced Countries |
| RDC | Rest of Developing Countries |
| RE | Renewable energy |
| ROR | Reliability, optimization, and resilience |
| RRA | Renewable resource assessment |
| R5ASIA | Asian Nations |
| R5LAM | Latin American and Caribbean |
| R5MAF | Middle Eastern and African |
| R5REF | Reforming 5 Economies Forum |
| SDEWES | Sustainable Development of Energy, Water and Environment Systems |
| SAF | Sustainable aviation fuels |
| SDG | Sustainable Development Goals |
| SDM | Systems dynamics modeling |
| SED | Sustainable energy development |
| SE4ALL | Sustainable Energy for All |
| SF6 | Sulfur hexafluoride |
| STEP | Stated and Planned |
| TIESR | New technology integration with energy storage requirement |
| TT | Technology transfer |
| UN | United Nations |
| UNEP | United Nations Environmental Protection |
| UNFCCC | United Nations Framework on Climate Change Convention |
| UNFCCC | UN Framework Convention on Climate Change |
| UNDESA | United Nations Department of Economic and Social Affairs |
| V2V | Vehicle-to-vehicle |
| WEA | World Energy Assessment |

# Chapter 1

# Introduction

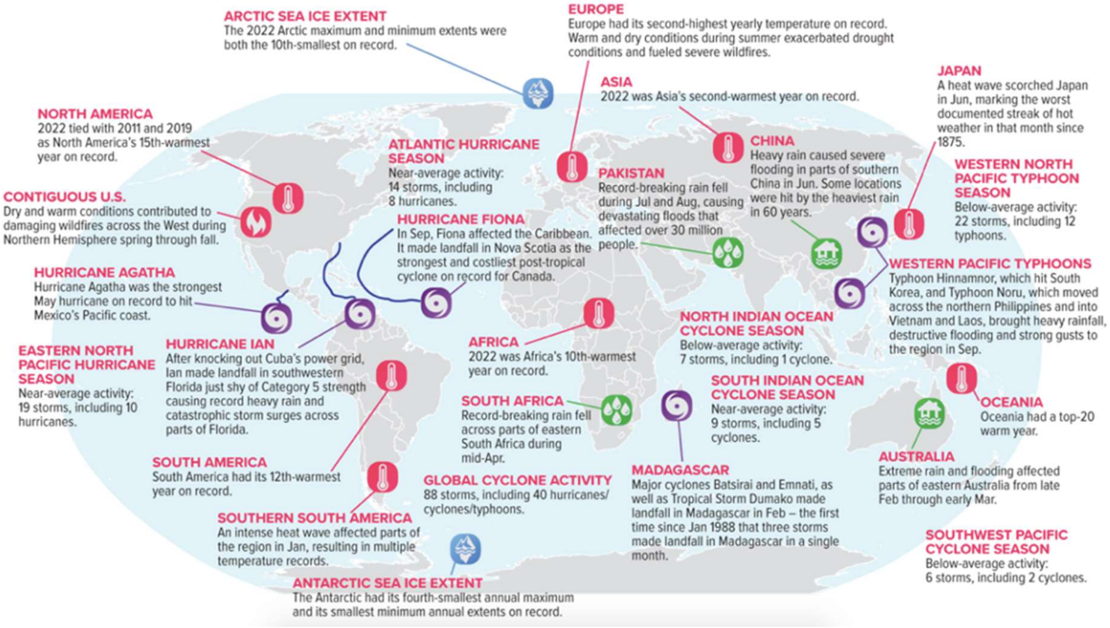
Submitted as: **Akpan J.**, Olanrewaju O. (2024) "Towards a Simplified and Integrated Model for Energy-Climate Resources and Systems Planning"
*Paper for the 12th International Conference on Smart Energy Grid Engineering (SEGE 2024), Ontario, Canada. (IEEE Xplore).*

## 1.1 Energy Development - Climate Crisis

*'We have to wake up to the fierce urgency of the now.'*
- Jim Young Kim, The World Bank President, 2014 [1]

The debate over climate crisis has continued to be the centre of discourse surrounding sustainable development, despite the large investment into activities that support sustainability principles and the continuous attempt towards the removal or deaccumulation of greenhouse gases (GHG) in the atmosphere to avert the immediate and long-term adverse effect of the accumulation. The main concern around the conversation has been that the current actions taken are not enough to combat the consequences of climate change. Beyond the insufficiency of the actions of the current paradigm, a further strain placed on protecting the environment is the reality that the resources and system demand is on an increasing side. This results in the clarity that only fierce and urgent actions need to be taken immediately to meet global supplies, rising demand, and environmental concerns in a sustainable way [1] and to avert further climate change damages, as depicted in Figure 1.1.

The transition to sustainable energy practices is a crucial step in reducing greenhouse gas emissions and curbing global warming, but several challenges and disparities hinder its effective implementation. The inertia within established energy infrastructures heavily reliant on fossil fuels due to vested interests, financial dependencies, and institutional frameworks favouring conventional energy sources is a primary issue. The scale and speed required to meet the growing demand for energy worldwide also pose a challenge. Renewable energy technologies have made significant advancements, but their capacity and efficiency may not match the scale of energy demand, especially in rapidly developing regions. The intermittent and storage limitations of renewable sources create hurdles in ensuring a consistent and reliable energy supply. Financial and infrastructural investments for adopting sustainable energy solutions pose barriers, particularly for economically disadvantaged communities and developing nations. Addressing this disconnect requires a multifaceted approach, including regulatory frameworks, subsidies, and international agreements, as well as continued research and development to improve the efficiency and storage capabilities of renewable sources. Collaboration among governments, industries, and communities is essential to resolve this disconnect, involving technological innovation, policy reform, financial incentives, and inclusive strategies to ensure equitable access to clean energy and align the demand for energy with sustainable practices to address the climate crisis.



**ARCTIC SEA ICE EXTENT**
The 2022 Arctic maximum and minimum extents were both the 10th-smallest on record.

**EUROPE**
Europe had its second-highest yearly temperature on record. Warm and dry conditions during summer exacerbated drought conditions and fueled severe wildfires.

**ASIA**
2022 was Asia's second-warmest year on record.

**JAPAN**
A heat wave scorched Japan in Jun, marking the worst documented streak of hot weather in that month since 1875.

**NORTH AMERICA**
2022 tied with 2011 and 2019 as North America's 15th-warmest year on record.

**ATLANTIC HURRICANE SEASON**
Near-average activity: 14 storms, including 8 hurricanes.

**CHINA**
Heavy rain caused severe flooding in parts of southern China in Jun. Some locations were hit by the heaviest rain in 60 years.

**PAKISTAN**
Record-breaking rain fell during Jul and Aug, causing devastating floods that affected over 30 million people.

**WESTERN NORTH PACIFIC TYPHOON SEASON**
Below-average activity: 22 storms, including 12 typhoons.

**CONTIGUOUS U.S.**
Dry and warm conditions contributed to damaging wildfires across the West during Northern Hemisphere spring through fall.

**HURRICANE FIONA**
In Sep, Fiona affected the Caribbean. It made landfall in Nova Scotia as the strongest and costliest post-tropical cyclone on record for Canada.

**WESTERN PACIFIC TYPHOONS**
Typhoon Hinnamnor, which hit South Korea, and Typhoon Noru, which moved across the northern Philippines and into Vietnam and Laos, brought heavy rainfall, destructive flooding and strong gusts to the region in Sep.

**HURRICANE AGATHA**
Hurricane Agatha was the strongest May hurricane on record to hit Mexico's Pacific coast.

**NORTH INDIAN OCEAN CYCLONE SEASON**
Below-average activity: 7 storms, including 1 cyclone.

**EASTERN NORTH PACIFIC HURRICANE SEASON**
Near-average activity: 19 storms, including 10 hurricanes.

**HURRICANE IAN**
After knocking out Cuba's power grid, Ian made landfall in southwestern Florida just shy of Category 5 strength causing record heavy rain and catastrophic storm surges across parts of Florida.

**AFRICA**
2022 was Africa's 10th-warmest year on record.

**SOUTH INDIAN OCEAN CYCLONE SEASON**
Near-average activity: 9 storms, including 5 cyclones.

**SOUTH AFRICA**
Record-breaking rain fell across parts of eastern South Africa during mid-Apr.

**OCEANIA**
Oceania had a top-20 warm year.

**SOUTH AMERICA**
South America had its 12th-warmest year on record.

**GLOBAL CYCLONE ACTIVITY**
88 storms, including 40 hurricanes/cyclones/typhoons.

**MADAGASCAR**
Major cyclones Batsirai and Emnati, as well as Tropical Storm Dumako made landfall in Madagascar in Feb – the first time since Jan 1988 that three storms made landfall in Madagascar in a single month.

**AUSTRALIA**
Extreme rain and flooding affected parts of eastern Australia from late Feb through early Mar.

**SOUTHERN SOUTH AMERICA**
An intense heat wave affected parts of the region in Jan, resulting in multiple temperature records.

**SOUTHWEST PACIFIC CYCLONE SEASON**
Below-average activity: 6 storms, including 2 cyclones.

**ANTARCTIC SEA ICE EXTENT**
The Antarctic had its fourth-smallest annual maximum and its smallest minimum annual extents on record.

**Figure 1.1.** Climate change consequence. According to the National Oceanic and Atmospheric Administration (NOAA) report [2]

The journey towards the 1.5°C climate scenario, the recent United Nations (UN) Conference of Parties (COP) 28, and planned follow-up action with the first global stock-taking appear complex. For instance, Maslin M. et al. [3] presented the outcome of the just concluded COP 28 [4] under five key outcomes. Drawing from the insight of the work by Maslin M. et al. [3] and based on the four pillars set by the COP28 presidency (i.e., fast-tracking a just, orderly, and equitable energy transition; fixing climate finance; focusing on people, lives and livelihoods; and underpinning everything with full inclusivity), Table 1.1 summarises these five outcomes, with corresponding resolution level and the implications.

**Table 1.1** Summary of the Key Outcomes of COP 28 and the possible implications. Source: Authors' elaboration.

| S/N | Key Outcome | Summary | Implications | Resolution Level |
|---|---|---|---|---|
| 1 | The end of fossil fuels? | • A complete acknowledgement of fossil fuel as the root cause of climate change.<br>• No concrete agreement on the complete phase-out of fossil fuels. | • Justification for continuous burning of fossil fuels with the use of emissions capture technologies | BAU, except with a little advancement towards emissions mitigation |
| 2 | Loss and damage | • The climate finance pledge for developing countries with most climate- related disasters fell overly short of the annual financial requirement.<br>• An endorsement of the declaration on climate relief, recovery, and peace is supported by 41 organisations and 71 governments (including the EU).<br>• The concession on this has been moved to COP 29 | • Continuous damages may be recorded across both the affected nations and new ones. | BAU, except with a little or almost no advancement to climate disaster management |
| 3 | Renewable energy and transitional fuels | • A pledge by 118 countries to triple RE capacity By 2030<br>• A pledge to double the global energy efficiency rate from 2 to 4% by 2030<br>• A pledge by industries to increase the share of hydrogen from renewables by 2030<br>• Nuclear energy and liquified natural gas are encouraged as transitional fuels.<br>• Endorsement by 22 governments to triple nuclear energy generation by 2050 | • Envisaged increasing rate of RE integration into national grids of countries.<br>• Continuous high financial investment into transitional fuels | BAU except with increased ambitions, yet less financial commitment |
| 4 | Oil and gas decarbonisation charter | • A net-zero decarbonisation charter involving (emissions from methane leakage, gas flaring, and direct operations) was signed by organisations representing approximately 40% of global oil gas production. | • Challenges of decarbonisation may continue with the rest of the 60% of organisations with a commitment to the charter. | An increased commitment towards decarbonisation |

| | | | | |
|---|---|---|---|---|
| 5 | Global stocktake – 1.5°C is at risk | - The first global stock-taking was done to show individual country's progress and commitment towards emissions mitigation.<br>- The required value of emissions to be mitigated towards the needed 1.5°C is still far. | - There would be a need for rapid response in emissions mitigation. Otherwise, the Paris Agreement of 2015 would remain an unaccomplished dream. | BAU, as there is no centralised agreement on emissions mitigation cap for each country |

BAU – Business As Usual (i.e. Baseline)

Though the outcome of the recent COP28, as shown in Table 1.0, may seem promising, it appeared not to have clearly and completely addressed the issues needed towards the desired climate scenarios, as the resolution levels are not too far from the present business-as-usual efforts of emissions mitigation. The outcomes of COPs are primarily meant to result in emissions mitigation progress towards the right climate scenario in protecting the environment. However, the attribution of the multi-faceted complex challenges of countries and regions continues to pose a challenge and has slowed this progress. Beyond the environmental advantages, as it has always been considered in literature and climate conversations, a framework to discuss the outcome of emissions reduction measures, future primary energy mix, future economic risks and benefits of achieving this endeavour would be useful in helping countries and organisations see the urgency and benefits of planning for emissions mitigation.

This thesis examines sustainable energy development in the climate crisis and believes that the solution lies not only in simply adopting new technologies but in the time value of policy decisions and in understanding the deep-seated diverse factors such as clean energy-climate investment attractiveness, environmental emissions commitment, and economic growth that shape our energy chain. The dissertation highlights several key issues with current energy practices that have not received sufficient attention in the energy transition debate. These include the centrality of emissions reduction commitment towards the 1.5 ºC climate scenario, energy finance towards climate change mitigation, the increase of interest in 100% renewable energy (RE) for all purposes, and the challenges posed by the intermittency of renewable energy sources. The thesis presents a narrative that these issues are not simply technical problems to be solved but are deeply intertwined with other factors. In order to address these issues, this thesis presents a more holistic approach to energy transition that takes into account the environmental emissions commitment, economic attractiveness, and least-Carbon dimensions of energy. Therefore, this includes introducing new emissions reduction policies, time value of emissions policies and energy practices that are more sustainable, just, and equitable, as well as the engagement in achieving full public interest in full transition renewable energy system and its benefits both in the short and long term. These approaches are necessary to address the complex energy diversity challenges faced today. Hence, it is important to move beyond superficial "techno-fixes" to contribute to developing a deeper understanding of the total dynamics of energy diversity as well as ensure just energy transition practices.

## 1.2 Energy Resources and Systems Diversity in Mitigating the Impending Climate Crisis

This thesis is built on the premise that the inclusion of a diverse range of energy resources and systems is of paramount importance in effectively tackling climate catastrophe. The diversity entails a harmonious balance of the current dominance of non-renewable energy resources and the integration of renewable energy resources, carbon removal, and low-Carbon technologies [5], [6], [7], [8], [9], [10]. The strategy of diverse energy resources and systems serves to reduce over-dependence on fossil fuels, which are the main catalysts of greenhouse gas emissions [6]. Through the integration of renewable energy resources such as solar, wind, and hydroelectric power, alongside the adoption of Carbon technological systems, a huge potential exists in the long term to substantially reduce carbon emissions while also upholding energy security and reliability [11]. Diversification serves as a protective measure against potential supply interruptions, geopolitical and regional conflicts, and price volatility that may arise from an overreliance on one energy source [6], [7]. The promotion of energy diversity could lead to a reduction in Carbon emissions [12] and also in enhancing resilience in response to the dynamic nature of climate change since the occurrence of severe weather events has the potential to interrupt energy infrastructure and supply [13]. A diversified energy portfolio that incorporates many sources exhibits more adaptability in addressing these difficulties, therefore assuring a reliable and uninterrupted energy supply in times of emergencies.

A comprehensive array of energy resources in a country’s or regional grid portfolio could easily facilitate the equitable transition, considering the energy requirements and unique capacities of countries and regions that strongly depend on certain energy sources [6], [7], [10]. The introduction and implementation of policies and strategies aimed at aiding the population impacted by the transition is of utmost importance. The achievement of energy diversity is crucial in addressing the difficulties posed by climate change and in establishing a reliable and sustainable energy infrastructure. Aligning regulatory frameworks and government policies to support energy diversity through subsidies, incentives, and other regulations could favour emerging energy sources, necessitating consistent balance and supportiveness for green energy towards mitigating climate change consequences.

In summary, the inclusion of a variety of energy resources and systems is crucial in addressing the climate problem, as it allows the opportunity for an integrated approach to energy production, encourages advancements in technology, stimulates economic development, and facilitates a fair transition process. The fundamentals of the perspective of the integrated approach and framework needed for the diverse energy resources and systems planning is what this thesis centres on, with insights drawn from existing theories, and philosophies. The rationale for this approach is presented in the next section.

## 1.3 Study Rationale - Integrated Assessment Approach Justification for Energy Diversity Issues.

Integrated assessment is distinct from traditional methods of assessment. As a result, different people inevitably interpret the idea differently [14]. However, the primary purpose of the use of IAM is to address problems that require interdisciplinary approaches [15], like interdisciplinary education knowledge sharing [14] and energy-climate economics [16]. The need for integrated assessment models has been growingly becoming very useful in guiding government policy decisions towards sustainable development since their use involves knowledge from different groups of researchers and professionals from different fields who use models in a combined form to solve key problems in society that may hardly be possible with a single discipline [17]. The present state of Integrated Assessment IA modelling is talked about, along with its background, features, and difficulties. It shows that managing uncertainty is a big problem and that different approaches are needed to work together to handle the different kinds of uncertainty [18], [19]. An approach for harmonising integrated assessment models to reduce model variance and uncertainty was proposed using a PARIS REINFORCE-based framework evaluated on six models [20]. The framework showed a reduction in model variance and offered diagnostic input on harmonisation quality, as shown by the findings. This harmonisation has continued to be the basis for the continuous development of emerging IAM tools to bridge these variances an in the incorporation of newer challenges such as breakthrough technologies and policies such as in the society and climate discussions. Integrating socioeconomic, technology and technical trends with environmental implications like climate change requires integrated assessment models (IAMs) [21]. To make (IAMs) more useful for reducing climate change, Wilson C. et al. [22] synthesise together different process-based integrated assessment models (IAMs) to suggest a methodical way to check whether IAMs are useful, trustworthy, suitable, and comprehensible for climate policy [22].

Most of the IAMs are concentrated on the effect of climate change because of the impact of changes in GHG emissions due to land use policies, dietary changes, fertilizers use, cultivation methods, and afforestation. The study by Harmsen et al. [23] recommends a set of metrics for assessing Integrated Assessment Models (IAMs) used in climate change mitigation efforts. Some examples of indicators include the transformation index, the relative abatement index, the emission reduction type index, and the cost per abatement value. The approach was applied to 17 IAMs, both new and old versions. The analysis shows how the indicators can indicate major gaps between models and link model behaviour to features and assumptions [23]. The integration of different integrated assessment and modelling components to handle complex environmental challenges is covered in work by Hamilton et. al [24], and as shown in Figure 1.2. It emphasizes how crucial it is to address key elements within the integrated assessment process, concerns, management alternatives, stakeholders, natural and human systems, as well as spatial and temporal scales, disciplines, techniques, models, tools, and sources of uncertainty [24].

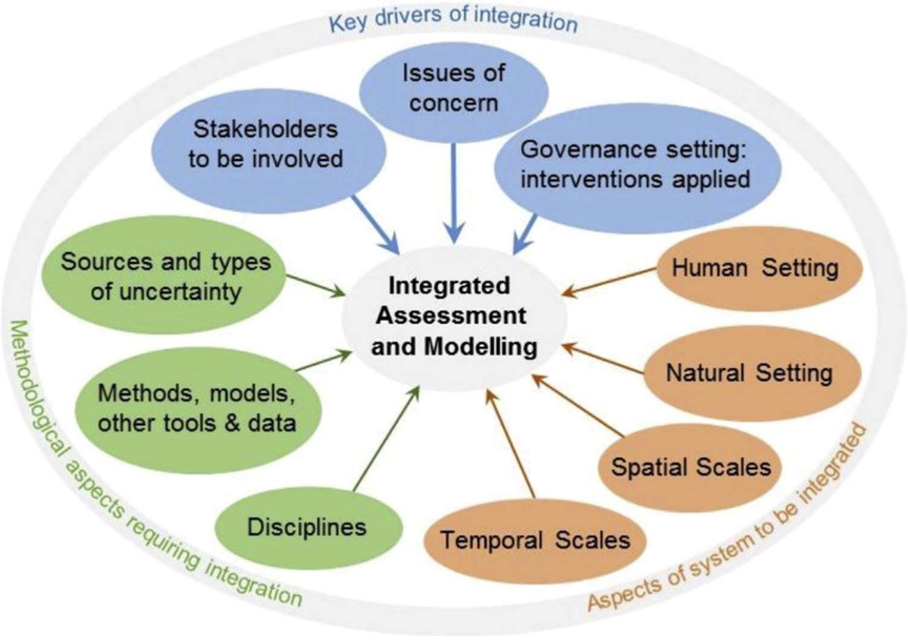


**Figure 1.2.** Typical elements of IAM. Based on Hamilton et al. work in [24]

The IPCC advises transparency and encourages open-source and web-publishing IAM documentation [21]. Consequently, this has given rise to the need for the use of non-black-box methodological approaches in IA modelling. Such IAM models are built on several principles, mainly on philosophy, fundamental knowledge, and science-based understanding and assumptions. Several IAM exist, and some of the popular which have been fully described [25], [26] include AIM, ASF, C-ROAD/EN-ROAD, E3ME, E3MG, ENTICE-BR, ENV-Linkages, FAIR, FUND, G-CUBED GINFORS, GEM CCGT, GEM-E3, GEMINI-E3, GINFORS, GTEM, ICLIPS, IGSM, IMACLIM, IMAGE, MDM-E3, MERGE, MERLIN, MESSAGEix-GLOBIOM, GCAM, MS-MRT, NEMESIS, PACE, PANTA-RHEI, PROMETHEUS, REMIND, Second Generation Model, TIAM, WILLIAMS, and WITCH. A typical example of the emerging concepts in IAM is the use of the principles of system dynamics for the society-environment-climate-energy IA models, such as in the C-ROAD/EN-ROAD Interactive models [27] and WILLIAMS model [28]. Systems dynamics modelling (SDM) is a concept invented by Jay Forester in 1961 and serves as a powerful tool for understanding and addressing complex challenges [29], such as sustainable development and energy climate change mitigation [30]. SDM is a methodology for understanding the behaviour of systems over time, considering the complex interactions between different components and feedback loops [31], [32]. A system here means a network of variables connected by causal relationships, exhibiting behaviour that can only be observed as a whole [32]. SDM is particularly well-suited for analysing these issues because it can capture the long-term dynamics and unintended consequences of decisions and policies. The key principles of systems dynamics modelling are depicted in Figure 1.3.

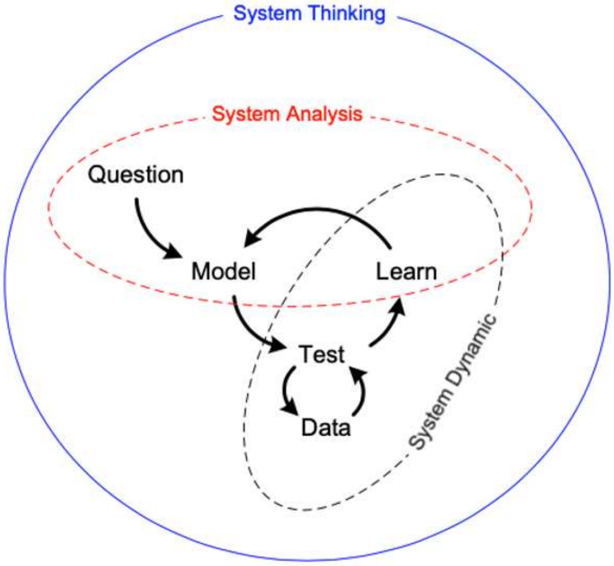


**Figure 1.3.** Key principles of SDM [33]

Using Systems thinking, i.e., the questioning and understanding of how everything is connected to everything else [32], [33], SDM emphasizes viewing issues as interconnected systems rather than isolated components. This holistic perspective is crucial for understanding the complex interactions that shape sustainable development, energy, and climate change mitigation. SDM recognizes that feedback loops for the model to learn and provide different outcomes, which may be positive or negative, playing a fundamental role in the behaviour of systems. Positive feedback loops amplify change, while negative feedback loops dampen change [33]. Understanding these feedback loops is essential for identifying leverage points for intervention [32], [33], [34], [35].

Scholarly curiosity has been piqued in the question of why society has failed to act upon the warnings of science and has, therefore, been unable to stop the environmental degradation that is occurring on Earth [36]. Hence, analysing the interactions between science, technology, and society is not only a very interesting field of study but also very useful in providing useful feedback towards a holistic governance framework for effective policy of managing the earth's resources. SDM models are useful in this regard, as they can typically be represented by the earth's stock and materials flow, which depict the accumulation and movement of resources over time. Stocks represent the accumulated level of a resource, while flows represent the rates at which resources are added or removed from stocks [33]. Hence, the earth's resources can be kept within its planetary boundaries and safe for humanity [37].

SDM offers several benefits and applications, shown in Table 1.2, for addressing complex challenges like sustainable development and energy climate change mitigation.

**Table 1.2.** Benefits and application of SDM. Source: authors' elaboration.

| Benefits | Description | Application | References |
|---|---|---|---|
| Integration of multiple and diverse perspectives | SDM models can incorporate diverse viewpoints and stakeholders, leading to more comprehensive and inclusive solutions | Analysis of the trade-offs between economic growth and environmental sustainability, identifying pathways towards sustainable economic development.<br>Simulation of the complex interactions between human activities, dynamics of different energy sources, greenhouse gas emissions, and climate change. | - |
| Identification of unplanned consequences | SDM models can reveal the long-term and unexpected outcomes of decisions and policies, helping to avoid unintended negative consequences. | The understanding of long-term implications of resource extraction and the accumulation of pollutants in the environment. | - |
| Supports for policy evaluation | SDM models can be used to evaluate the effectiveness of proposed policies and identify areas for improvement. | Assessment of the economic, social, and environmental impacts of different climate change mitigation options, enabling informed decision-making. | [38], [39] |
| Facilitation of stakeholder engagement | SDM models can serve as a platform for communication and collaboration among | Exploration of the distributional impacts of environmental policies and identifying strategies through public and | [38], [40], [41] |

| | | |
|---|---|---|
| | stakeholders, promoting shared understanding and consensus-building. | stakeholders' participation for ensuring that the transition to a sustainable future is equitable and just. |

## 1.4 Problem Statement and Model Framework Formulation

Energy is a crucial component of modern living environments, and its production to consumption significantly impacts the environment depending on the energy intensity of the resources used. The energy sector continues to account for an annual average of about 70 % of total GHG emissions [42]. With Russia's invasion of Ukraine, ambitious energy policies, technical advances, and energy security concerns are speeding clean energy transitions [43]. However, fossil fuels still supply around 80% of primary energy, according to the 2023 IEA energy technology perspective report [44]. Beyond the deployment of clean energy technologies, sustainability in the sector relies on effective and efficient improvements in several other areas [45], [46], [47]. Since the energy - climate challenge has been seen as a diverse issue already discussed in section 1.2, identifying the key areas of energy development would be useful in effectively addressing the concern of climate change. A typical illustration of the essential factors that link energy and climate is represented in the causal diagram of Figure 1.4, which is common with IAM such as WILLIAMS and C-ROADS/EN-ROADS models.

The relationship between energy growth and energy consumption is shown to be positively correlated, whereby a rise in one variable leads to a corresponding increase in the other. This interdependence creates a positive feedback loop, which may be used to analyze future possibilities by examining historical data. While the applicability of this finding may vary at the nation level, global data consistently supports the veracity that energy growth and energy consumption are proportionate. The supply of energy is subject to certain limitations, and as a result, excessive energy use may lead to an energy deficit that hampers economic development. Therefore, it can be seen that positive feedback leads to exponential development, whereas negative feedback destabilizes the system. The availability of energy is contingent upon the presence of both renewable and non-renewable energy resources since their availability directly impacts the overall energy supply. The physical limitations of these two energy supplies must be taken into account to safeguard against potential disruptions to energy supply, which might have adverse consequences on energy scarcity, energy consumption patterns, and overall economic development. Over time, the inherent constraints associated with non-renewable energy sources have given rise to energy deficits, hence necessitating the exploration and advancement of renewable energy alternatives. The persistent use of non-renewable resources has resulted in heightened hazards associated with climate change, hence necessitating the expansion of infrastructure dedicated to renewable energy sources. In the event of substantial economic growth, it becomes possible to allocate additional resources towards the development of renewable energy infrastructure, as well as research and development efforts aimed at achieving significant advancements in energy storage technology. These endeavours, alongside other breakthroughs, can contribute to enhancing the availability of renewable energy sources, thereby aiding in the mitigation of climate change impacts resulting from elevated levels of $CO_2$ concentration.

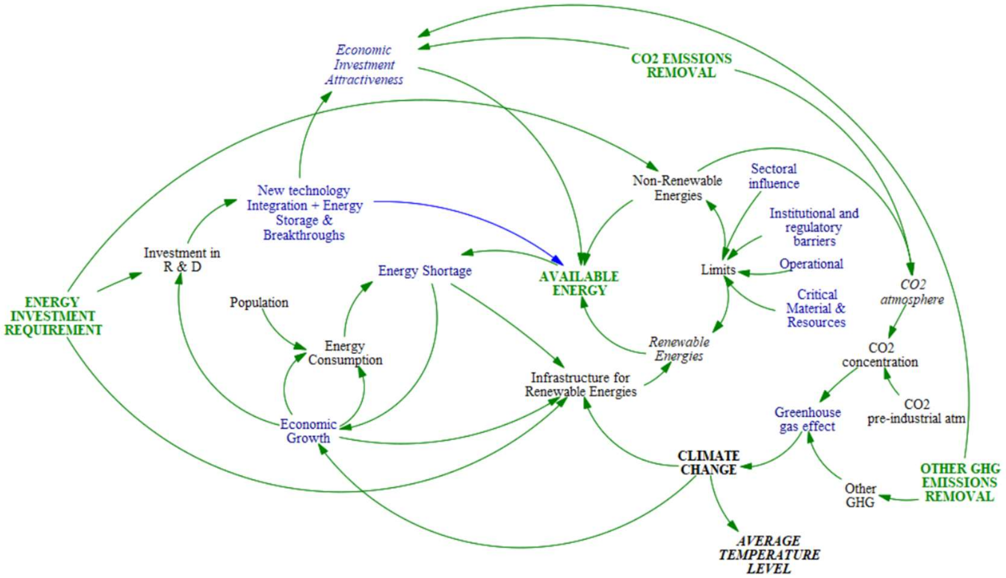


**Figure 1.4.** A conceptual overview of a simplified, integrated Energy-Climate model. Source: Author's Elaboration.

Towards achieving sustainability of the earth, the energy sector has continuously been faced with intense pressure to cut its environmental impact profile as countries seek ways to meet climate mitigation targets set out in the Paris Agreement [48] and the IPCC recommendation of keeping the temperature rise between 1.5 - 2.0ºC [49], [50], [51]. The long-term temperature increase has been reduced by about 1°C as a result of increased policy momentum and technological advancements gained since 2015 [43]. However, the non-centrality of NDC and current country-disjoint policy goals of reducing annual $CO_2$ emissions is not enough to prevent the extremely damaging effects of climate change [43]. With various technologies, regulatory approaches, management strategies, and policies, the environmental impact of emissions has been well-acknowledged to affect climate indices such as temperature rise level, sea level, and other phenomenon [38], [52], [53], [54], [55], [56]. In this research, the focus is mainly on the use of just and fair emissions reduction policy simulation towards an average global temperature rise level of 1.5 ºC using systems dynamics modelling principles to establish scenarios useful for further analysis: discussing areas which have been hardly analyzed in existing energy-climate IAMs. These areas include the economic attractiveness and time value of each scenario, as climate ambitions are often regarded as highly expensive [57]. In addition, 100% renewable energy towards mitigating climate change has been scarcely discussed in IAM tools; hence, introducing a more holistic perspective is pertinent.

Given the robustness of the SDM principles already presented in the preceding section and the complexity of the issues in energy-climate discussions, this thesis leverages the advantages of SD and, in addition to other useful methodologies to explore three key models (i.e., environment, economic, and energy depicted in Figure 1.5) development that could be integrated into existing and or established IAMs. In addition, the findings from the individual models from this thesis are also useful in energy systems and resource planning towards sustainable practices needed to ensure that the climate scenarios are kept within the IPCC-defined limits of not more than 1.5 to 2.0 °C temperature rise levels.

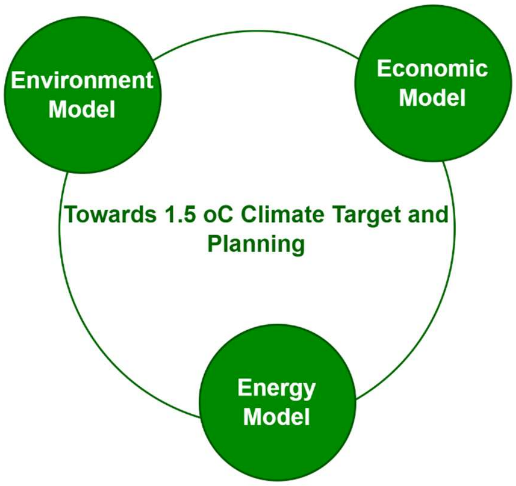


**Figure 1.5.** Theoretical framework. Source: author's elaboration.

## 1.5 Aim and Objectives of the Model and Framework

The integrated model and framework in this study are aimed at providing different scenarios and insights needed to guide both public and climate policymakers, private investors, energy consumers, and IA modellers towards the sustainable planning and management of diverse energy resources and systems. As the world faces increasingly complex environmental challenges, IAMs would play an increasingly important role in informing policy decisions. The integrated models can be used to study the complex interactions between human activities, the environment, energy, and the economy, as introduced in the preceding section - section 1.4 of this thesis. It seeks to address the following research questions with the corresponding objectives as follows:

*a) Environment Model*

Question 1 What are the long-term outcomes of different climate change mitigation and adaptation strategies on global temperature rise levels, and what is the way forward?

Objective 1.1 To present state-of-the-art knowledge in climate change mitigation-related areas under sustainable energy development, including mitigation, adaptation strategies, and reduction policies.

Objective 1.2 To simulate the effects of different emissions reduction policies on greenhouse gas emissions and climate change indices (i.e., global temperature rise level) using the integrated assessment tool.

Objective 1.3 To propose different pathways that can help facilitate the transition to the best climate scenarios.

b) *Economic Model*

Question 2 What are the economic risks, costs, and benefits of different environmental policies?

Objective 2.1 To develop an economic model using the pathway proposed in O.1.2 that analyses the economic attractive of the different policies from O.1.1

Objective 2.2 To apply the model of O.2.1 to other illustrative cases in ascertaining the economic benefits of the policy options for each case.

c) *Energy Model*

Question 3 How can we develop more sustainable and equitable energy systems needed to meet the climate scenario targets?

Objective 3.1 To demonstrate the concept of a direct relationship between sustainable energy and the climate scenario targets using impacts of different sectoral policies on greenhouse gas emissions using an existing integrated assessment tool.

Objective 3.2 To present a review and perspective towards a common methodology and modelling tool for analysis of transition into the suitable climate scenarios and the 100% renewable energy for all purposes.

## 1.6 Methodological Approach

The methodological approach used in this thesis is founded upon the IPCC recommendation of the incorporation of transparency and open science for IAM [21], aimed at using suitable science-proven methods in a more transparent, experience-based, open-source data and models in developing new approaches [58] for research practice. Peters M. [58] emphasized open science practices using seven propositions, as stated in Table 1.3, based on certain theories. Recently, Leonelli S. [59] evaluated these propositions and other open science principles and practices as playing vital roles within contemporary research and its relations to the epistemology of science. Based on a process-oriented perspective of research as a tool for policy decision-making, the work by Leonelli S. [59] frames openness as the pursuit of appropriate linkages among systems of practice, such as would be useful for policy evaluation of practices that are integrated approaches or strategies.

**Table 1.3.** The foundation of the seven prepositions of open science philosophy. Based on the work by Peters M. [58]

| Preposition | Description | Theory Reference | Theory Reference |
|---|---|---|---|
| Openness to 'experience' | The preposition focuses on the research's practical considerations. | This preposition might be viewed in an empiricist, inductive, and Baconian manner. | [60] |
| Openness to criticism | This preposition offers the necessary framework for research to allow an engagement in the rational critique of reasons for practical consideration of research results. | The extension and naturalization of the Kantian account of Reason | [61] |
| Openness to interpretation | The preposition under discussion has profound roots in historical contexts related to self-expression, free speech, and other academic liberties that embody research. | - | - |
| Openness to the Other | An ethical position that might be understood in the context of the current era as institutionalizing peer research production, allowing information to be freely shared, and working together to establish the intellectual commons | - | - |
| Open science communications technologies | The view of contemporary research as evolving into open-source and open-access science models based on distributed knowledge systems and an ethic of sharing, peer review, cooperation, and collaboration | - | - |
| Openness = freedom | The view of open data and information as the building blocks upon which creativity (the intellectual commons) and innovation are built. | The extension of Openness to interpretation and Openness to the Other | - |
| Open science governance | The implementation of peer review to encompass all levels of the professoriate, as well as users, including the public. | - | - |

Generally, in open science philosophy, there are two key categories of methodological approaches for obtaining research results: the confirmatory and the exploratory approaches [62], [63], [64]. These two approaches can be employed separately or in a combined form.

Within these two categories, quantitative or qualitative analysis can be made through the support of experiments, inquiry, simulation, models and frameworks developments, and other methods or tools application. Exploratory (i.e., hypothesis-generating research) approaches endeavour to establish connections between concepts to uncover the underlying reasons behind probable cause-and-effect interactions. This phenomenon arises when the comprehension of the nature of observations during the construction of cause-and-effect models. A confirmatory (i.e., hypothesis-confirming or hypothesis-testing research) approach refers to a kind of investigative approach in which a substantial understanding of the phenomenon under study has been established and well documented. In the context of research, it is common to formulate one or more ideas and, after that, aim to ascertain if these theories are substantiated by empirical evidence.

According to the esteemed scholar J.W. Tukey, “it is essential to use both exploratory and confirmatory methodologies since the process of formulating the question has more significance than arriving at an answer”.

This thesis work uses both the confirmatory and exploratory approaches, as shown in Table 1.4, to address the research questions and objectives from section 1.5.

**Table 1.4.** Research methods

| Model | Methodological Approach | Method and Rationale | Hypothesis | Applicable Theory Reference |
|---|---|---|---|---|
| Environment | Confirmatory approach | Kaya Index and Existing IAM that suit the requirement of open science philosophy discussed in this section | Formulation of policy scenarios to determine the amount of GHG per policy within the target year | Cause -Effect: Systems Thinking |
| Economic | Confirmatory approach | Author-developed method. | Utilization of policy scenarios from the environment model to ascertain the economic attractive per policy within the target year | Cost-Benefit Concept from Capital Budgeting Technique |
| Energy | Exploratory approach | Demonstration of the concepts using an existing IAM that suits the requirement of open science philosophy discussed in this section | Formulation of policy scenarios to establish concepts to uncover underlying factors per policy within the target year | Cause - Effect: Systems Thinking |

The research hypothesis used in this study, as highlighted in Table 1.3, is used to explore scenarios to answer the research questions in this study by comparing different paths to the future. The three models are based on a predetermined set of inputs, including hypotheses and policies, which define a specific scenario used to examine the potential consequences of different hypothetical futures rather than to make predictions.

In order to ascertain the different global temperature levels and climate scenarios of the different hypotheses for the environmental model, emission reduction measures were done using the C-ROADS policy simulator, working on the principle of system thinking. The outcome of the reduction measures is confirmed to be in line with scenarios from the published outcomes of international climate studies from several organizations. From the results of the emission reduction measures, further studies using a novel model integrating capital budgeting techniques were carried out to determine the investment attractiveness and economic risk of the resulting global temperature levels and climate scenarios.

In employing a confirmatory approach, the model's behaviour is made to align with real-world observations, such as GDP growth influencing inflation and project costs. Thus, the model and analytical approach in this economic model indicate promising applications to examine the economic attractiveness of carbon reduction programs in various nations, cities, and organizations. Hence, the model was applied to the emissions budgets for China, the USA, India, and the European Union (EU).

The last model (being a perspective model) was to synthesize and explore how the global energy system would evolve given the hypothetical futures of 100% renewable energy systems using an existing system thinking tool. The synthesized hypothesis was then introduced to determine mainly the projection of future emissions value, global primary energy mix, and global temperature levels scenarios.

This research hypothesis is robust and can be used to address uncertainties in many contexts where many interacting factors make it difficult to examine how the system may evolve.

These hypothesis scenarios are in line with some of the Intergovernmental Panel on Climate Change (IPCC) and other organizations' scenarios, showing credible depictions of future developments, based on logical and internally coherent assumptions about the progression of influential social and economic factors.

## 1.7 Significance of the Thesis and Contribution to Knowledge

The environmental model incorporates the concepts of fair transition to assess the equitable contributions that each country and region can make towards achieving the 1.5°C Climate scenario. With this concept, the current National Determined Contribution (NDC) across countries that have been inadequate towards meeting the 1.5°C climate target can leverage this simplified principle to transform the current practice into a more inclusive and fair sharing ratio for all countries that are party to the commitments.

The economic model presented in this thesis can be linked to pre-existing integrated assessment models (IAMs) due to its capacity to analyse the investment desirability of climatic scenarios and the temporal significance of policy choices. With the utilization of the principles of capital budgeting, this thesis developed a novel integrated emissions cost budgeting model. The purpose of this model is to assess the financial viability of several policy scenarios aimed at achieving the 1.5ºC climate objectives. The cost-benefit analysis approach evaluates the economic attractiveness associated with financing requirements and strategies aimed at reducing emissions. The use of this approach served to exemplify the attractiveness of clean energy and climate investments as effective measures against climate change.

Furthermore, this approach was implemented across five global scenarios and included four prominent nations, namely China, the United States, India, and the European Union. The model envisages applicability in other cases such as in emission budgeting scenarios for energy investment across cities, in households, Carbon intensive production processes, and a host of other possible emissions-driven projects. The narrative of the economic model in this thesis serves to bridge the gap between the evaluation of economic implications of emissions reduction and the achievement of the 1.5°C climate goal within the energy and climate-integrated models.

The approach outlined in this thesis is anticipated to make a valuable contribution to the existing body of literature by emphasizing and integrating emissions budgeting. Additionally, it offers further research considerations that shed light on the direct relationship between sectoral contributions, technological advancements, and the transition towards achieving the 1.5ºC target and net-zero emissions.

The energy model has facilitated the transformation of several pre-existing methodologies into potential avenues for adopting a unified approach and modelling tool. This tool would allow the representation of a comprehensive transition planning and strategy towards achieving 100% renewable energy, capable of keeping the climate scenario even below a temperature rise of 1.5ºC.

## 1.8 Limitation and Data Statement

The thesis has created new data based on the different information syntheses, the developed model and the existing ones used. The analysis provided supports the validity of the hypothesis and scenarios generated. However, most of the input data are from the verified C-ROADS/EN-ROADS models, serving as the primary basis, while other data sources used have been declared as well. Hence, the validity of the final data from the thesis is dependent on the trustworthiness of the separate data sources.

## 1.9 Summary and Structure of the Thesis

The chapter is structured into six chapters:

**Chapter 1** introduces the work with energy – climate crisis background, energy resources and systems diversity to addressing the climate crisis, addressing the energy diversity challenges using integrated approaches and IAM, and the usefulness and emergence of systems thinking in IAMs. Then, the research problem and rationale for model formulation are presented, showing that the areas in the thesis are centred based on the identified gaps. Research questions are presented with corresponding objectives, methodological approaches used in the thesis, the significance of research contribution, limitations, and finally, the thesis structure and conclusion.

**Chapter 2** outlines the history of sustainable energy development, with areas that are more related to the climate scenarios to present the background for answering the research questions.

**Chapter 3** addresses the first research question: What are the potential long-term consequences of various policies aimed at mitigating and adapting to climate change in terms of their impact on global temperature increase, and what are the recommended pathways to be taken in the future? In order to achieve this, the impact of different policy options on climate scenarios is simulated, and a discussion of possible pathways is made to conclude the chapter.

**Chapter 4** centres on the second research question of what are the economic risks, costs, and benefits of different environmental policies by developing a simplified economic model using the pathway proposed in chapter 3 to analyse the economic attractiveness of various policy options. The model is then validated with the application of other illustrative case studies to determine the economic benefits of the new policy options for each of those case studies.

**Chapter 5** presents the general rule for renewable energy integration, providing the basis for introducing and discussing different evaluation mechanisms and indices that would be useful for doing a comprehensive 100% RE analysis. It then leverages the identified

evaluation mechanisms to suggest modelling considerations in 100% RE analysis, and then reviews the tools used in RE studies and their suitability for 100% RE studies. The limitations of the existing tools are identified and proposed key elements that an ideal energy modelling tool for 100% RE should exhibit are presented.
This chapter is aimed at providing insight into developing a more sustainable and equitable energy system needed to meet the climate scenario targets.

**Chapter 6** provides an overall conclusion of each of the 5 chapters by summarising each of them and then presenting the direction for future studies.

# Chapter 2

## Sustainable Energy Development: History and Recent Advances

Published as: **Akpan J.**, Olanrewaju O. (2023) "Sustainable Energy Development: History and Recent Advances"
*Journal: Energies* [65]

### 2.1 Introduction

There is an anticipated decline in global oil demand from 2022 to 2028 because of the ongoing energy transition and a peak in fossil fuel combustion at around 100 million barrels per day, as shown in Figure 2.1. The acceleration of this economic slowdown has been facilitated by the invasion of Ukraine by Russia and the post-COVID-19 recovery spending plans implemented by governments. According to numerous projections from international organizations and government agencies, which were compiled and compared by R. Daniel et al. [66], oil demand is envisaged to have a substantial decline by the year 2050. This decline is expected to plateau during the 2030s, ultimately resulting in a level that is partly consistent with achieving global climate objectives [67]. According to the evolving policy scenarios, the projection shows a decrease in oil demand within a range of 20 – 25 million barrels per day by the mid-century [66], given the rise and anticipated massive adoption of renewable energies in the bid to reduce the global carbon footprint from the $CO_2$ associated with fossils fuels. This move is part of the United Nations (UN)'s drive to achieve sustainable development.

Consequently, an earlier discussion in the ''Our common future'' report in [68] from the United Nations underlined the importance of energy in attaining sustainable development (a concept described as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"), with the year 2000 seeing the beginning of the concept of sustainable energy.

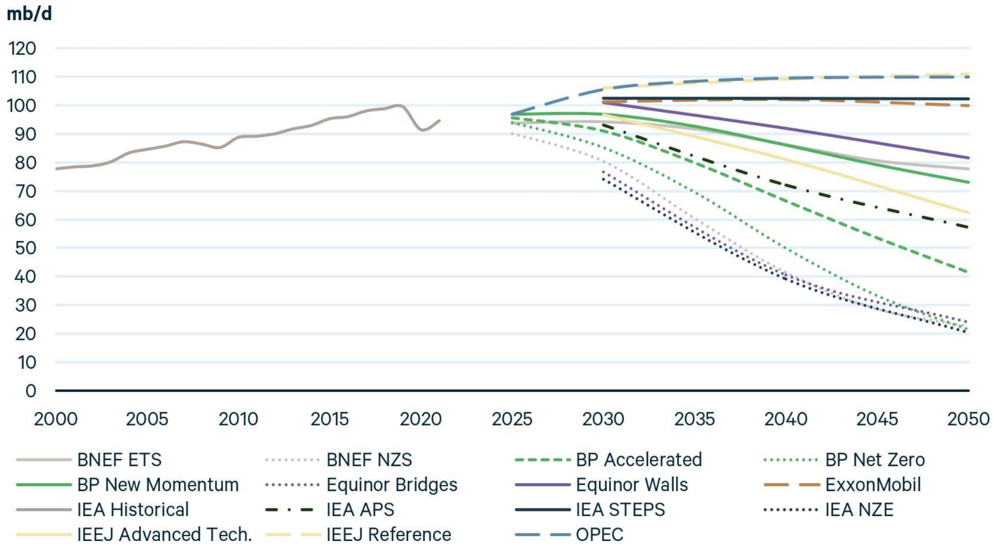
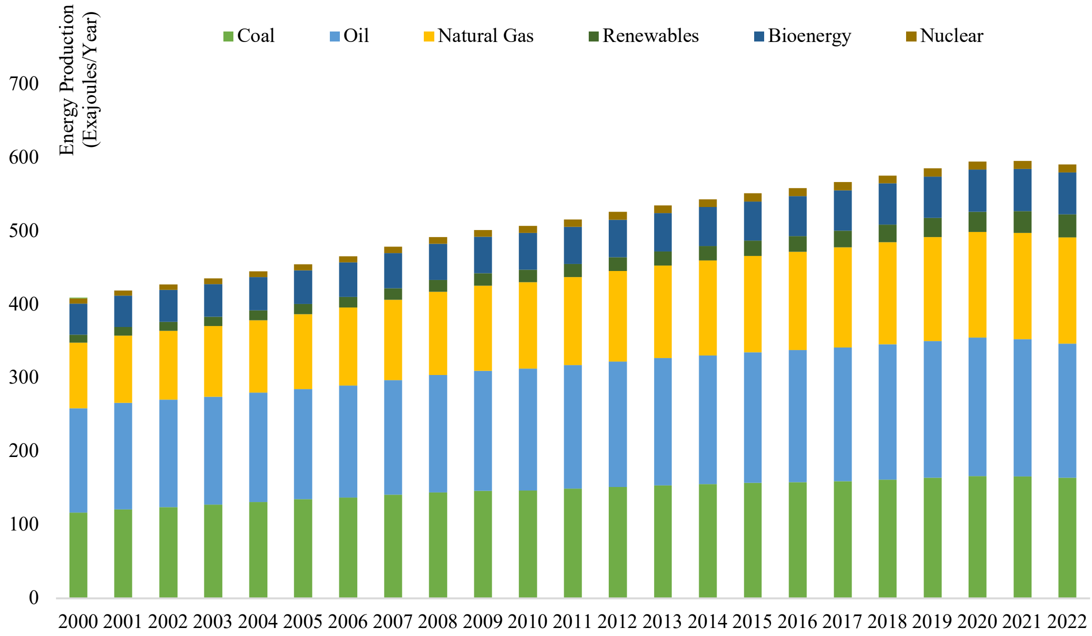
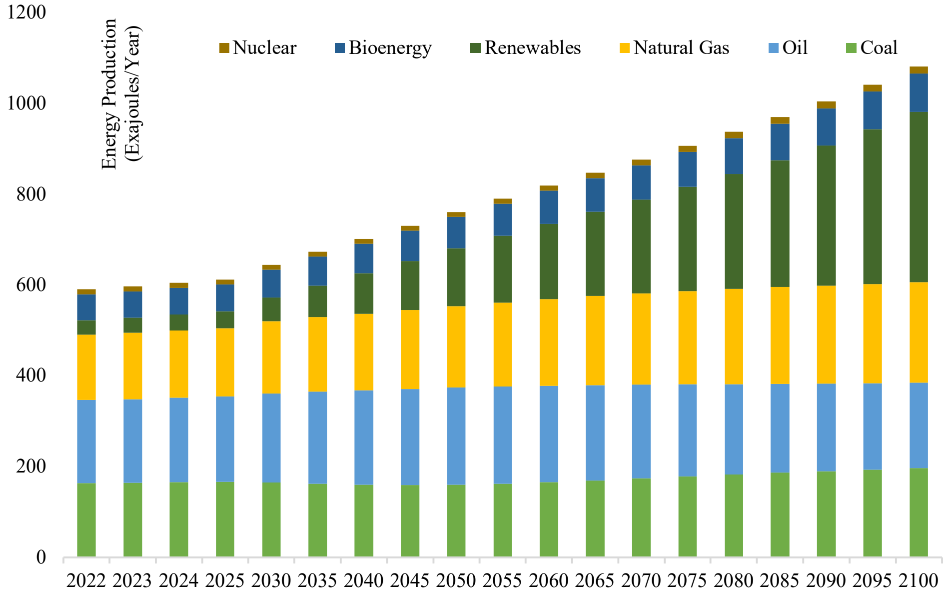


**Figure 2.1**. Global oil demand and peak assessment (compilation of scenarios from different bodies and international agencies), according to R. Daniel et al. in [66]

While global oil prices show a decline in demand in succeeding years, other fossil energy sources have also been predicted to experience a reduction in supply and demand, with a growth in renewable energy for utilization. These predictions are displayed in Figure 2.2 below.



(**a**)



(**b**)

**Figure 2.2.** Global primary energy mix. Data from Climate Interactive in [27] based on IEA and British Petroleum reports in [43] [69], respectively. (**a**) Historical path; (**b**) Forecasted path.

## 2.2 Structure of the Chapter

This chapter is structured in seven sections. The first section introduces the work, the history of SED and critical discourse on the summary of existing reviews on SED are presented in the second and third Sections, respectively. The fourth Section reveals the rationale behind this chapter, while the fifth Section synthesizes and discusses the selected SED themes. The fifth Section focuses on energy financing under the 1.5 °C scenario and presents updated national energy policies. In addition, The fifth Section introduces the rise in the desire to reach 100% renewable energy (RE), with some issues and challenges, particularly for developing countries without 100% electrification. The limitations of reaching 100% RE are numerous, forming most emerging energy issues, including energy war and energy storage. An overview of energy storage technology is presented in the subsequent sixth Section. In the sixth Section, SED progress, including emerging issues and the interconnections between energy security, innovation, climate change, and financing for sustainable development, is discussed. The seventh Section explores the intersection between energy, climate change, and innovation. The conclusion, with possible areas of further research areas, is included in the last Section.

## 2.3 Contribution of the Chapter

This chapter contributes to the literature by presenting the state-of-the-art direct knowledge in the history of sustainable energy development as well as synthesis of the different areas of SED scattered across literature into themes, and the ones in direct line with the 1.5°C climate scenarios of the Intergovernmental Panell on Climate Change are identified for further discussion. First, energy financing towards the 1.5°C climate scenario is explored and followed by the 100% renewable energy interest. The later is discussed in line with emerging issues like energy affordability/accessibility, energy war and energy storage. The energy storage technologies are compared, and emerging decarbonization strategies across the building, transport, industrial, and power sectors are categorized and presented.

## 2.4 History of SED

Sustainable energy development (SED) is a concept introduced by the United Nations World Energy Assessment (WEA) report that considers energy development's economic, social, and environmental aspects [70]. The United Nations' WEA report highlighted the significance of not "exceeding the carrying capacity of ecosystems" regarding energy production and use. It also stressed how critical it is to have a reliable, low-cost source of electricity [70]. Since then, SED has been a global policy priority to address the issues plaguing the modern energy sector, such as the depletion of fossil fuels, increasing energy consumption, and global warming [71]. Notably, over the years, there has been a growing interest in and increasing strategies aimed at achieving sustainable development from the energy sector. The historical development of energy and sustainable development was first highlighted by I. Gunnarsdottir et al. in [71]; hence, an updated and more detailed history is presented in Table 2.1, extracted from an original supplementary part of the work by J. Akpan and O. Oludolapo in [72].

**Table 2.1.** The historical path of energy versus sustainable development with key selected reports.

| Year | Protocol and Description | Ref. |
|---|---|---|
| 1972 | Stockholm Meeting<br>The first international meeting devoted to global environmental issues, which led to the formation of the Brundtland Commission. | [73] |

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|---|---|---|
| 1974 | International Energy Agency (IEA)<br>A year after the Stockholm meeting, a global oil crisis occurred in 1973. In response to the global physical disruption in oil supplies, IEA, under the framework of the Organization for Economic Co-operation and Development (OECD), was formed to compile data on the international oil market with the aim of promoting energy efficiency and conservation and fostering international technological cooperation for research and development. Subsequently, there have been relevant energy reports and world energy outlooks from the IEA.<br>• The 1998 editions used a "business-as-usual" approach, focusing on energy trends without new policies.<br>• The 2001 edition extended its projection horizon to 2030.<br>• The 2003 edition quantified global energy investment needs.<br>• The 2004 edition questioned the sustainability of the current energy systems.<br>• The 2005 edition assessed energy prospects in the Middle East and North Africa, focusing on China and India.<br>• The 2009 edition analyzed the financing of energy investment under a post-2012 climate framework, global natural gas markets, and energy trends in Southeast Asia.<br>• The 2010 edition presented a scenario that considered recent commitments to tackle climate change and worsening energy insecurity, focusing on renewable energy technologies, unconventional oil, climate policies, Caspian energy prospects, energy poverty, and energy subsidies.<br>• The 2011 report noted that emerging economies' oil demand for transport grew by almost 50%.<br>• The 2012 edition featured new projections extended to 2040.<br>• The 2017 edition introduced the Sustainable Development Scenario, a major new scenario aimed at achieving internationally agreed objectives on climate change, air quality, and universal access to modern energy.<br>• The 2018 edition focused on producer economies and the impacts of the COVID-19 pandemic on the energy sector.<br>• The 2020 edition worked through energy financing and funding.<br>• The 2022 edition focused on the implications of the ongoing energy crisis triggered by Russia's invasion of Ukraine.<br>• The 2023 edition focused on oil analysis and forecasting to 2028.<br>• The 2023 edition looked at world energy investment (yet to be concluded). | [74][75][75] |
| 1987 | Our Common Future—Brundtland Report<br>At the Brundtland Commission meeting, sustainable development was introduced, with energy being an integral part of the concept, because of concerns about the global oil crisis. | [68] |

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| 1988 | International Climate Negotiations—Intergovernmental Panel on Climate Change (IPCC)<br>The United Nations Environmental Protection (UNEP) Agency sought an international convention to provide direction for restricting greenhouse gas emissions while improving energy and industrial processes and driving sustainable development. Then, the IPCC was formed, which has, since its establishment, made public findings from the scientific community and summarized them in the following reports, which were more specific to energy and sustainable development. These include the following:<br>• IPCC Report of 1994 (Guidelines for National Greenhouse Gas Inventories);<br>• IPCC Report of 1994 (Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios);<br>• Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories<br>• IPCC 2000 (Emission Scenarios);<br>• IPCC 2001 (TAR Climate Change 2001—Mitigation);<br>• IPCC 2005 ($CO_2$ Capture and Storage);<br>• IPCC Report of 2006 (Guidelines for National Greenhouse Gas Inventories);<br>• IPCC 2007 (IPCC Report of 1994 (Guidelines for National Greenhouse Gas Inventories);<br>• 2007 AR4 Synthesis Report—Climate Change;<br>• 2007 AR4 Mitigation of Climate Change;<br>• 2011 Renewable Energy Sources and Climate Change Mitigation;<br>• 2014 AR6 Synthesis Report—Climate Change;<br>• 2022 AR6 Climate Change—Mitigation of Climate Change;<br>• IPCC 2018 (Global Warming of 1.5 degree Celsius);<br>• IPCC Report of 2019 (Refinement to 2006 IPCC Guidelines for National Greenhouse Gas Inventories);<br>• 2022 AR6 Climate Change;<br>• 2023 AR6 Synthesis Report—Climate Change. | [76] |
| 1992 | UN Agenda 21<br>Following the Brundtland report Our Common Future, the IPCC's formation, and the identification of the importance of energy, an action plan was developed that was discussed in more detail in the UN Kyoto Protocol of 1997. | [70] |
| 1992 | UN Framework Convention on Climate Change (UNFCCC)<br>As a result of the action plan developed by the UN Agenda 21, countries made a global commitment to work together to develop solutions to limit rising global average temperatures, and the UNFCC was founded. | [77] |
| 1995 | Conference of Parties (COP)<br>The Conference of the Parties (COP) is the highest decision-making body for the UNFCC, which first held its meetings in Berlin every year (with this year's known as COP28, to be held in Dubai, UAE), involving delegates from all parties' countries, | [78] |

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|---|---|---|
| | meeting to assess the convention’s effectiveness through evaluating national communications and emission inventories of countries working towards sustainable societies. | |
| 1997 | UN General Assembly<br>The 1997 UN General Assembly emphasized sustainable energy production, distribution, and use for improved sustainable development. The UN Commission on Sustainable Development focused on atmosphere, energy, and transport in 2001. | [79] |
| 1997 | UNDP Kyoto Protocol<br>A protocol was developed to ensure financial assistance for clean energy projects under the Clean Development Mechanism (CDM), which emphasizes that organizations must engage in sustainability practices to be able to receive funding for energy programs and projects. | [80] |
| 2000 | UN Millennium Declaration<br>In September of 2000, world leaders signed the United Nations Millennium Declaration, committing to work together to end extreme poverty, hunger, disease, illiteracy, environmental degradation, and gender discrimination. However, sustainable energy targets were not included in the declaration. | [81] |
| 2000 | UNDP World Energy Assessment Report<br>The first proposal for sustainable energy development was introduced in this assessment report. | [70] |
| 2001 | UN Commission on Sustainable Development (CSD-9)<br>The UN Commission on Sustainable Development was birthed from the UN 1997 General Assembly, which proposed CSD-9 to focus on atmosphere, energy, and transport. | [82] |
| 2002 | UN World Summit on Sustainable Development<br>Following the establishment of UN CSD-9, the world’s first summit on sustainable development was held in Johannesburg, where the concept of a sustainable energy development initiative was discussed and adopted, alongside another set of activities that considered respect for the environment, with ten-year regional and national sustainable production and consumption programs being proposed. | [83] |
| 2003 | UN World Summit on Sustainable Development report<br>A report on the UN World Summit on Sustainable Development discussion was released. | [83] |
| 2004 | UN-Energy<br>Following the UN World Summit on Sustainable Development, the UN Energy inter-agency mechanism was established to aid countries in transitioning to sustainable energy by accelerating roadmap implementation, especially through the activities listed in the resolution of the UN World Summit on Sustainable Development report.<br>Consequently, this initiative called for existing and newly created energy organizations at the national, regional, and international levels to come together to work towards sustainable development. | [83] |
| 2005 | Energy Indicators for Sustainable Development | [84] |

| | | |
|---|---|---|
| | Five international agencies and organizations (United Nations Department of Economic and Social Affairs (UNDESA), International Energy Agency (IEA), International Atomic Energy Agency (IAEA), European Environment Agency (EEA), and Eurostat), recognized worldwide as leaders in energy and environmental statistics and analysis, presented a set of indicators for sustainable energy development. | |
| 2009 | International Renewable Energy Agency (IRENA)<br>IRENA, an international organization promoting renewable energy adoption and sustainable use, was formed to ensure that both industrialized and developing countries' needs are addressed.<br>• 2023 Edition—World's Energy Transition Outlook (1.5 °C pathway);<br>• 2021 to 2023—Tracking SDG 7, the energy progress report. | [85] |
| 2010 | UN Millennium Development Goals follow-up resolution<br>As a follow-up to the outcome of the Millennium summit and the declaration of 2000, energy was recognized and stressed as necessary for achieving the MDGs and sustainable development. | [86] [81] |
| 2011 | UN Sustainable Energy for All (SE4ALL)<br>UN initiative focused on advancing sustainable energy development.<br>Presently, the SE4ALL has become an international organization that works with the UN and leaders in government, the private sector, financial institutions, civil society, and philanthropies to accelerate Sustainable Development Goal 7 (SDG7)—access to affordable, reliable, sustainable, and modern energy for all by 2030—in line with the Paris Agreement on climate change | [87] |
| 2015 | UN 2030 Agenda for Sustainable Development<br>The SDGs were first introduced, with energy and climate change established as an integral part of sustainable development, with SDG 7 for energy and SDG 13 for climate change actions. | [88] |
| 2015–present | Development of SDG Trackers<br>As a result of the responsibilities for stocktaking and progress measurement of implementation towards sustainable development achievements, different organizations have used the targets and indicators from the UN 2030 Agenda for Sustainable Development to build platforms to assess the progress levels of countries.<br>2015 and later years to present—Research on SDG indicators' assessment and composition.<br>2019—SDG tracker systems and platforms. | [89], [90] |
| 2016 | National Determined Contribution (NDC)<br>The Lima COP agreed to cut emissions using collective and collaborative efforts under the concepts of NDC referenced in Article 4(2) of the Paris Agreement. | [91][48] |
| 2018–present | Stocktaking for National Determined Contribution (NDC)<br>Following the Paris Agreement's framework, mandates were created for countries to submit revised and enhanced nationally determined contributions (NDCs) in 2020 and every five years after that. In addition, beginning in 2023, signatories to the agreement | [92] |

| | | |
|---|---|---|
| | are enjoined in a global stocktaking of progress towards reducing global CO2 emissions every five years. | |
| 2019–present | Emerging New Global Energy System<br>Many discussions revolve around emerging global energy systems because of the several issues governing energy, such as the following:<br>i. Energy finance and justice/equity in relation to climate goals.<br>ii. Aligning climate change and sustainable development finance through the lens of the SDGs.<br>iii. The proximity in time to 2030 and sustaining of the 1.5–2.0 °C threshold for global warming.<br>iv. Inflation and energy war (as of September 2022, a third of the wealthy world’s inflation rate of 9% is attributable to energy due to Russia’s invasion of Ukraine);<br>v. Upsurge in 100% renewable energy investigations.<br>vi. Emerging fuels and technologies (energy storage and hydrogen technologies). | Author’s elaboration |
| 2023 | IEA World Energy Investment<br>Alongside the issues mentioned regarding the need for a new emerging energy system, IEA’s support of the Paris Agreement’s first global stocktake has resulted in a need for a world energy investment path. The upcoming UN Climate Change Conference, COP28 UAE, is expected to be held at Dubai Expo City from 30 November to 12 December 2023. The conference represents the culmination of the first global stocktake of the Paris Agreement. | |
| 2023 | 1st African Climate Summit<br>The first-ever Africa Climate Summit on 4–6 September 2023, in Kenya, focused on clean energy and industrial financing and Africa’s negotiating their stance in the global discourse ahead of COP 28 for mitigating climate change consequences, being the most affected continent. | |

## 2.5 Summary of Existing SED Reviews

In 2020, Gunnarsdottir et al. [71] studied the evolution of SED. They concluded from the several studies reviewed that the primary objective of SED is linked to achieving global sustainable development. This link involves the connection between several themes, such as energy security, sustainable energy use, affordable access to modern energy services, and sustainable energy supply. Z. Guzović et al. [93] summarized a compilation of papers published in a leading journal dedicated to selected papers from the series of SDEWES conferences to summarize recent advances in the development of sustainable energy systems. Five key domain areas were identified: energy policy analysis, energy conservation, cogeneration or polygeneration, alternative energy resource use (biomass in this case), and energy and environmental sustainability. Kabeyi M. and O. Olanrewaju, in their study in [94], combined the characteristics included in the Johannesburg definition in [83] with those listed in the International Atomic Energy Agency (IAEA) definition in [95] to present four primary themes for the promotion of sustainable energy development. These themes include energy efficiency improvement, energy security improvement, environmental impact reduction, and increasing energy accessibility, availability, and affordability.

Accordingly, in 2022, a systematic literature review on SED was carried out by Łukasiewicz et al. [96], highlighting three activities key to achieving SED, which were identified and discussed. These include the switch to more renewable energy sources in the global energy mix, lessening its negative effects on the environment and human health, and sustainable energy use through increasing energy efficiency measures.

During the current year of this study, D. Morea et al. [97], in a short editorial, reviewed selected papers promoting SED and presented possible future research directions for SED, which included the development of energy management protocols to address the behavioural barriers of energy-vulnerable households, optimal and even allocation of risks and penalties to energy stakeholders, and critical assessment of expenditures for global climate change actions. Other areas highlighted were energy diversification into capture and utilization technologies through the development of pricing, cost, and clear emission reduction estimation mechanisms for the utilization and promotion of $CO_2$ capture technologies and the evolution of development and energy security in fossil-fuel-dominant energy communities.

Finally, the analysis by X. Pan et al. in [98] made use of bibliometrics to gather the existing literature on the topic of energy and sustainable development and draw connections between the various pieces of information. In this work, climate change, energy's relationship with other SDGs, planetary boundaries, nexus informatics, economic growth, and energy consumption were the interconnected categories found.

Therefore, expanding upon the existing themes of SED to capture these newly identified areas needed to facilitate SED, Table 2.2 presents themes of SED and categorizes them into new SED themes in Table 2.3.

**Table 2.2.** Themes of SED (based on selected existing review studies of SED).

| Year of Study | Review Method | Sub-Themes | Main Themes Nomenclature | Ref. |
|---|---|---|---|---|
| 2021 | Citation analysis of most cited energy | • Energy security [1]<br>• Sustainable energy use [2] | 1, 2, 3, 4 | [71] |

| | | | | |
|---|---|---|---|---|
| | development studies | • Affordable access to modern energy services $^{3}$<br>• Sustainable energy supply $^{4}$ | | |
| 2022 | Two-decade overview of studies from SED conferences and special issues | • Energy policy analysis $^{5}$<br>• Energy use and conservation $^{2}$<br>• Co/poly generation and energy efficiency $^{6}$<br>• Alternative energy resource $^{7}$<br>• Energy and environmental sustainability $^{8}$ | 5, 2, 6, 7, 8 | [93] |
| 2022 | Critical review of sustainable energy transition strategies | • Energy efficiency improvement $^{6}$<br>• Energy security improvement $^{1}$<br>• Environmental impact reduction $^{8}$<br>• Increasing energy accessibility, availability, and affordability $^{3}$ | 6, 1, 8, 3 | [94] |
| 2022 | A systematic literature review (Analysis of studies from selected energy journals) | • Rise in renewable energy penetration in the global/national mix $^{7}$<br>• Energy and environmental sustainability $^{8}$<br>• Energy efficiency $^{6}$ | 7, 8, 6 | [96] |
| 2023 | Bibliometric | • Climate change $^{8}$<br>• Energy with other SDGs $^{9}$<br>• Planetary boundaries $^{8}$<br>• Nexus informatics (energy-water-land-food) $^{9}$<br>• Economic growth $^{9}$<br>• Energy consumption $^{2}$ | 8, 9, 2 | [98] |
| 2023 | Editorial | • Energy use management $^{2}$<br>• Energy stakeholders' accountability $^{3}$<br>• Energy innovation and carbon capture/sequestration technologies development $^{7}$<br>• Energy-related development contribution $^{9}$<br>• Energy financing for climate change mitigation $^{10}$ | 2, 3, 7, 9, 10 | [97] |
| 2023 | Critical discourse | • Identification of all SED themes from existing reviews (Synthetization and Categorization)<br>• Main discussion on the rise in renewable energy penetration in the global/national mix $^{7}$<br>• Main discussion on Energy financing for climate change mitigation $^{10}$ | 1 - 10 | This Chapter |

The numbers 1 to 10 are nomenclatures used to show the commonality and similarities with each sub-theme from different studies reviewed in Table 2.2, which are rearranged and placed in the applicable category in Table 2.3.

**Table 2.3.** Categorization of SED themes. Source: authors' elaboration.

| Theme No. | Sub-Themes | Main Themes |
|---|---|---|
| 1 | • Energy security<br>• Energy security improvement | Energy security |
| 2 | • Sustainable energy use<br>• Energy use and conservation<br>• Energy consumption<br>• Energy use management | Energy use |
| 3 | • Affordable access to modern energy services<br>• Increasing energy accessibility, availability, and affordability<br>• Accountability to energy stakeholders | Accessibility, affordability, and availability |
| 4 | • Sustainable energy supply | Energy supply |
| 5 | • Energy policy analysis | Energy policy |
| 6 | • Energy efficiency<br>• Energy efficiency improvement<br>• Co/poly generation and energy efficiency | Energy efficiency |
| 7 | • Alternative energy resources<br>• Rise in renewable energy penetration in the global/national mix<br>• Energy innovation and carbon capture/sequestration technologies development | Decarbonization |
| 8 | • Energy and environmental sustainability<br>• Environmental impact reduction<br>• Climate change<br>• Planetary boundaries | Environmental protection |
| 9 | • Economic growth<br>• Energy with other SDGs<br>• Nexus informatics (energy-water-land-food)<br>• Energy-related development contribution | Energy-X nexus |
| 10 | • Energy financing for climate change mitigation | Energy finance |

For the energy-X nexus, X can be other infrastructural areas such as land, water, food, information, and communication technology.

All ten themes from Table 2.3 are related to the environmental, social, and economic dimensions of industries linked with energy, forming the basis of SED, as shown in Figure 2.3. Recent reviews, such as the one discussed in Section 2.3, have focused more on sustainable energy use, affordable access to modern energy services, sustainable energy supply, energy policy analysis, co/poly generation and energy efficiency, alternative energy resources, energy and environmental sustainability, energy stakeholders' accountability, energy innovation and carbon capture/sequestration technologies development, and energy-related development contribution.

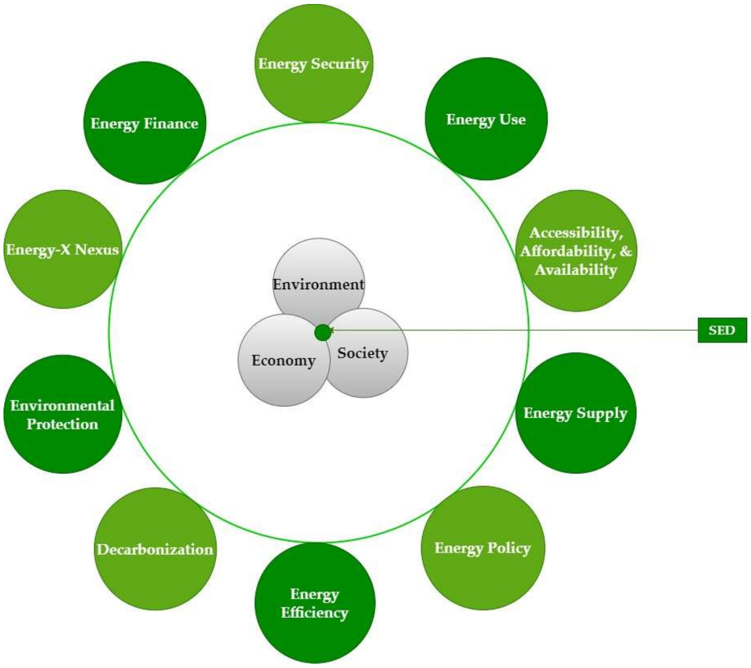


**Figure 2.3.** Themes of SED. Source: author's elaboration.

The next section in this chapter discusses the current updates regarding themes not discussed extensively in existing SED reviews, mainly energy financing for climate change mitigation and the rise in renewable energy penetration in the global/national mix, which are key decarbonization strategies, as well as the more recent advances or emerging global issues in SED, such as energy war and energy storage options. To foster economic and social growth with environmental benefits in all countries, SED requires considering all these themes in energy resource and system planning, implementation, and management.

## 2.6 SED Theme Synthesis

### *2.6.1 Energy Financing towards the 1.5 – 2.0 °C Scenario*

The energy sector is a key driver for global sustainability, economic growth, and climate change mitigation. Sustainable energy transition has been hastened by government support for renewable energy projects, which has encouraged private sector investment and diversified foreign investment portfolios. This section presents governmental financial pledges for energy development regarding global investment portfolios. Investment portfolios worldwide have become more diversified because of changes in the energy balance of countries and their growing preference for renewable energy. The extracted energy types are organized into five categories, as shown in Table 2.4 below.

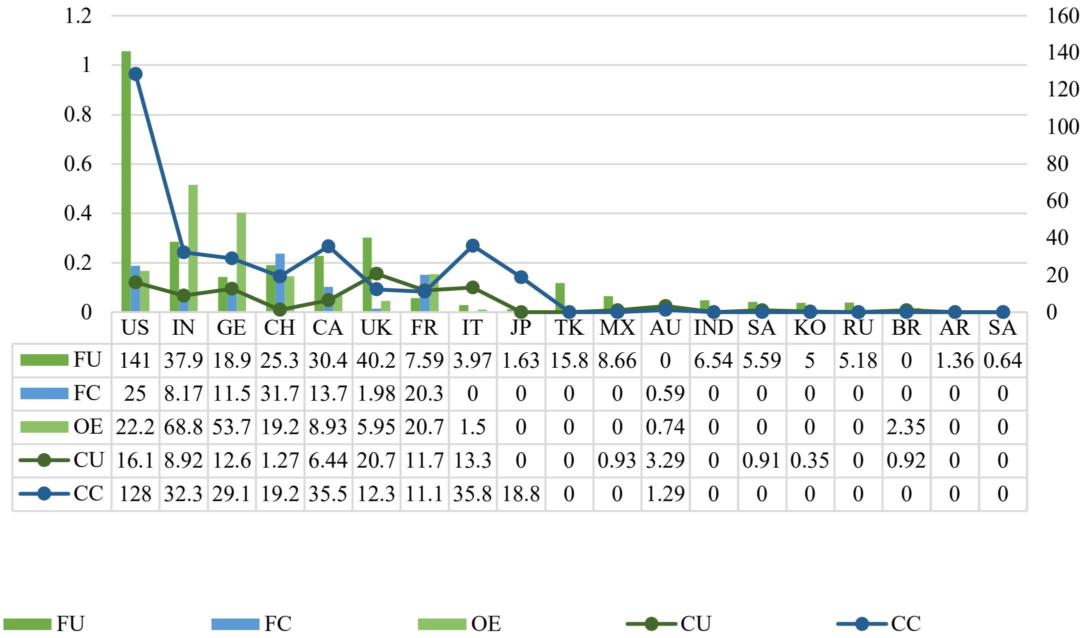
**Table 2.4.** Highlights of energy types of categorization and public funding commitments by the G20 (2020–2021).

| S/N | Energy Type | Description | Public Funds Commitment (USD Billion) |
|---|---|---|---|
| 1 | Fossil conditional (FC) | • Policies that encourage the development and consumption of fossil fuels, such as oil, gas, coal, "blue" hydrogen, or fossil-fuel-based power.<br>• Policies that also incorporate climate targets or additional pollution reduction obligations. | 113.19 |
| 2 | Fossil unconditional (FU) | • Policies that encourage the development and consumption of fossil fuels, such as oil, gas, coal, "grey" hydrogen, or fossil-fuel-based power.<br>• Policies that do not incorporate any climate targets or extra actions for pollution mitigation. | 357.78 |
| 3 | Clean conditional (CC) | • Potentially clean policies that declare willingness to assist in the transition away from fossil fuels but lack specificity about adopting necessary environmental protections during their implementation. | 326.13 |
| 4 | Clean unconditional (CU) | • Policies that consider only an unconstrained and unrestrained state of cleanliness, including renewable energy and "grey" hydrogen.<br>• Policies that support the production or consumption of energy are distinguished by being low-carbon and having little environmental impact. | 98.46 |
| 5 | Other energy type (OT) | • Policies that cross over between the two categories of "fossil" and "clean" energy.<br>• Policies that encourage the use of incineration, hydrogen from ambiguous sources, and a combination of both fossil and clean energy sources.<br>• Policies that encourage the use of nuclear energy, including uranium mining and "first generation" biofuels, biomass, and biogas, despite their well-known detrimental impacts on the environment. | 204.11 |

Data extracted from the energy policy tracker in [99]

In addition to many other programs, the government also pledges substantial sums of funds to support various forms of energy. In Table 4, fossil unconditional takes the largest share, whereas clean unconditional takes the least.

Figures 2.4 and 2.5 outline the different post-COVID-19 public investment commitments by energy type from the G20 (excluding the entire EU) extracted from the energy policy tracker [99]**.** In Figure 2.4, a considerable amount (highlighted in Table 4) of the public funds are committed to clean energy investment. It is distributed across the G20 countries alongside the other three energy types of public investment funds. However, the investment values have shown that all these countries' commitment to fossil investment is higher than their commitment to clean energy, except for Germany, Italy, Japan, and Australia, which have a greater percentage share in clean energy investment, with a total clean investment of 33.16%, 89.98%, 92.03%, and 77.50%, respectively, of their total energy investment. However, these clean investments with higher shares are conditional; for instance, Japan's investments are more on nuclear and do not specify and quantify how much carbon footprint could be reduced in the implementation process. At the same time, other countries' commitments, such as Italy and Australia, lack the same target quantification but only indicate support for a transition away from fossil dominance.



| | US | IN | GE | CH | CA | UK | FR | IT | JP | TK | MX | AU | IND | SA | KO | RU | BR | AR | SA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FU | 141 | 37.9 | 18.9 | 25.3 | 30.4 | 40.2 | 7.59 | 3.97 | 1.63 | 15.8 | 8.66 | 0 | 6.54 | 5.59 | 5 | 5.18 | 0 | 1.36 | 0.64 |
| FC | 25 | 8.17 | 11.5 | 31.7 | 13.7 | 1.98 | 20.3 | 0 | 0 | 0 | 0 | 0.59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OE | 22.2 | 68.8 | 53.7 | 19.2 | 8.93 | 5.95 | 20.7 | 1.5 | 0 | 0 | 0 | 0.74 | 0 | 0 | 0 | 0 | 2.35 | 0 | 0 |
| CU | 16.1 | 8.92 | 12.6 | 1.27 | 6.44 | 20.7 | 11.7 | 13.3 | 0 | 0 | 0.93 | 3.29 | 0 | 0.91 | 0.35 | 0 | 0.92 | 0 | 0 |
| CC | 128 | 32.3 | 29.1 | 19.2 | 35.5 | 12.3 | 11.1 | 35.8 | 18.8 | 0 | 0 | 1.29 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

G20 Public Funds Commitment (USD Billion)

**Figure 2.4.** Distribution of public funds commitment to energy investment (between 2020 to 2021). Data extracted from the energy policy tracker in [99]**.** US (United States), IN (India), GE (Germany), CH (China), CA (Canada), UK (United Kingdom), FR (France), IT (Italy), JP (Japan), TK (Turkey), MX (Mexico), AU (Australia), IND (Indonesia), SA (South Africa), KO (South Korea), RU (Russia), BR (Brazil), AR (Argentina), SA (South Africa). The legend FU, FC, OE, CU, and CC are for fossil unconditional, fossil conditional, other energy types, clean unconditional, and clean conditional, as explained previously in Table 4.

The total amount allotted to clean energy is 38%, smaller than fossil fuels at 43%, while other energies are 19%, as depicted in Figure 2.5. Energy investments, especially those in fossil fuels, are fraught with risks that may be mitigated by private funding for clean energy development. Tackling issues such as policy consistency, regulatory predictability, and regional inequities is crucial for maximizing the positive effects of the contribution that private finance makes to the energy industry. For a sustainable energy future that protects investor interests and promotes economic growth, striking this balance is essential.

Energy development projects financed by public funds have created opportunities for private sector investments in renewable energy, green technologies, and related industries. Integrating sustainable energy investments into global portfolios has become more attractive to investors seeking long-term returns and aligning with environmental, social, and governance (ESG) principles.

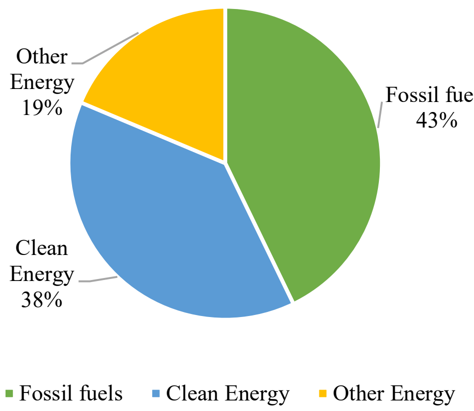
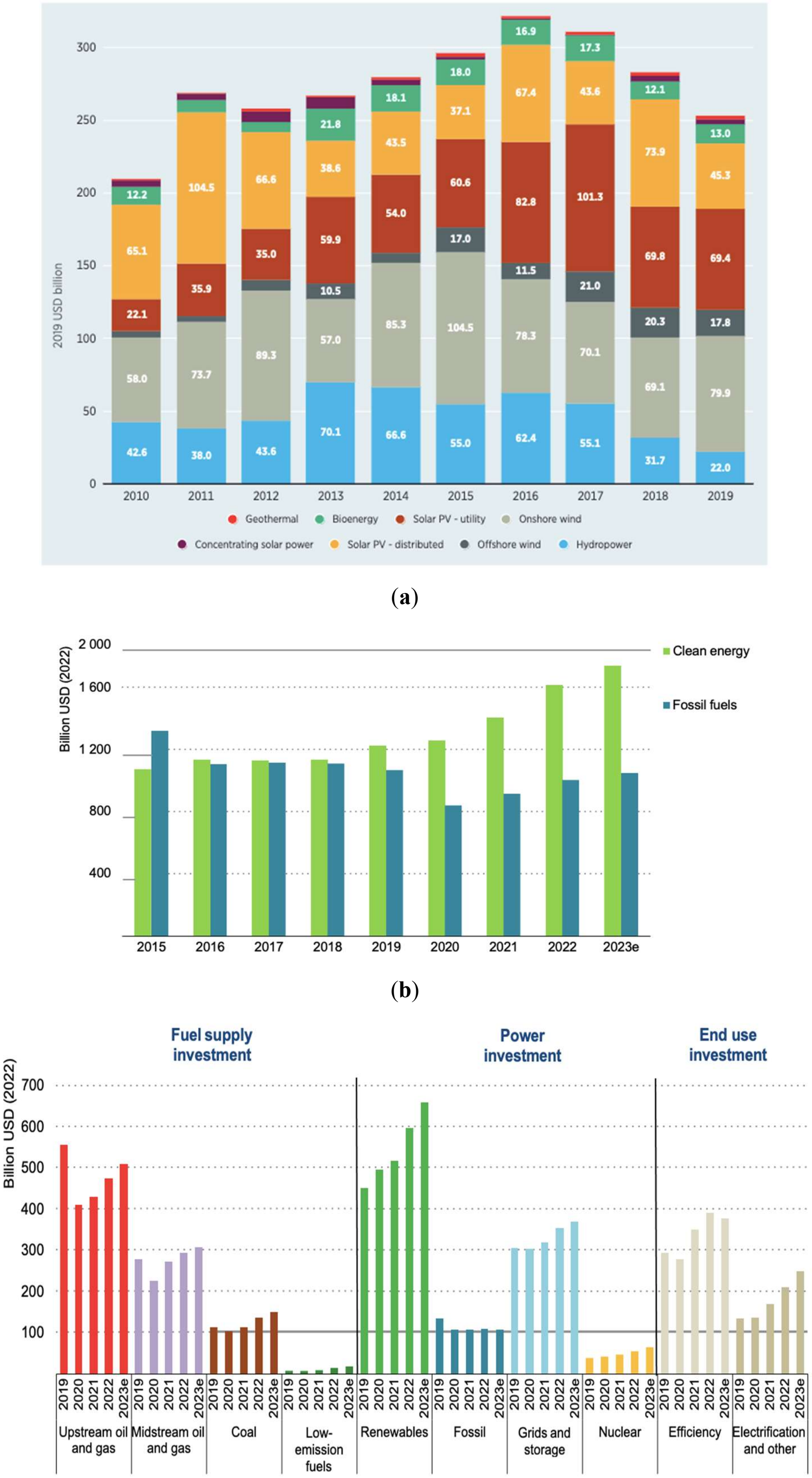


**Figure 2.5.** Total share of commitment of public finance to energy investment (1.09 USD Trillion) (in 2020–21)
Source: Author's elaboration.

Public finance for renewable energy is crucial due to the better value for money and environmental benefits it provides. In 2010, the global investment value of renewable capacity was USD 210 billion, with 88 GW added, while in 2019, twice as much new renewable energy production capacity was put into operation, with overall investment only rising by one-fifth to USD 253 billion. In addition, utility-scale solar PV dominated deployment capacity, accounting for 60% of all solar PV investment in 2019, whereas investments peaked in 2013 for CSP, hydropower, and biofuels [100]. These investment values of added RE installations are shown in Figure 2.6 a. In contrast, the investment commitment for energy projects is compared to RE and fossil fuels in Figure 2.6 b, with Figure 2.6 c highlighting the investment cost distribution across the different industrial sectors, with projections made for the current year - 2023.



(a)

(b)

(c)

**Figure 2.6.** Global energy investment. (**a**) The investment value of newly installed RE capacity (2010–2019), according to the IRENA report in [100]; (**b**) global total investment commitment for clean energy versus fossil fuel projects (2015–2023), according to the IEA report in [40]; (**c**) global investment distribution for clean energy versus fossil fuel projects (per industry/sector) (2019–2023), according to the IEA report in [57].

In 2022, the global expenditure on energy transition technologies reached an unprecedented sum of nearly USD 1.6 trillion (i.e., USD 1,600 billion, as in Figure 2.6 b). However, given the objective of limiting global temperature rise to below 1.5°C, it is necessary to increase this annual investment [57], [66], [67], [101], with [101] suggesting a cumulative amount of USD 150 trillion; hence, the projected expenditure to achieve this objective is estimated to surpass USD 5 trillion annually from the present time until the year 2050. In sustaining the current investment trajectory, securing an additional cumulative investment of USD 47 trillion is necessary by the year 2050. This amount is in addition to the estimated investment of USD 103 trillion, as projected in the Planned Energy Scenario, as shown in Figure 2.7. The annual investment of nearly USD 1 trillion in fossil-fuel-based technology should be redirected towards energy transition technologies and infrastructure [101].

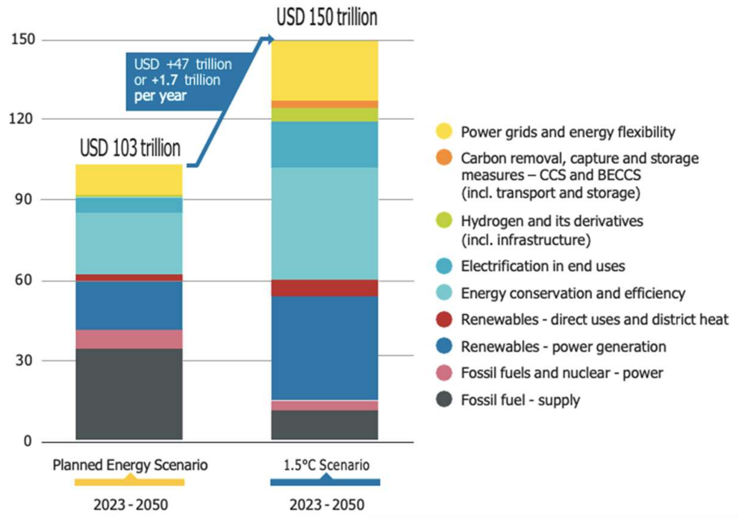


**Figure 2.7.** Global energy investment (planned energy scenario versus 1.5 °C scenario), according to the IRENA report in [101].

The relationship between public finance commitment to energy development and global investment portfolios is intricate and increasingly relevant in the context of climate change mitigation and sustainable development. Understanding this connection becomes essential as governments prioritize energy transition and investors seek to align their portfolios with environmental goals. Research and analysis in this field can help policymakers and investors make informed decisions that balance financial objectives with sustainability and long-term economic stability.

Based on Figure 2.5, which shows a total amount of USD 1.09 trillion in public finance commitment by the G20 to global energy investment, the amount is believed to facilitate progress towards energy security. However, in the context of the transition to clean energy utilization, and assuming the possibility of the total public commitments going into clean energy, with the same annual contributions between 2023 and 2050, a total of USD 29.43 trillion can be gained for clean energy investments. This amount is compared with the two scenarios in Figure 2.5 and represented in Figure 2.8 for comparative purposes.

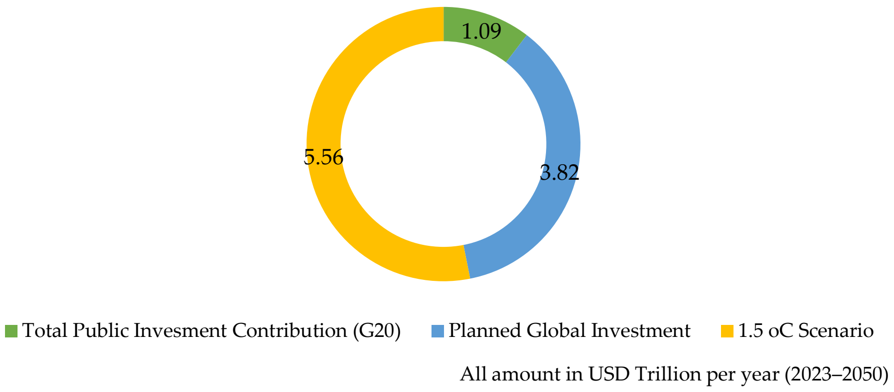


**Figure 2.8.** Global portfolio versus G20 public funds commitment to energy investment. Source: author's elaboration.

Given the difference between the total public investment contribution under the 1.5 °C scenario and the additional amount valued at 4.47 USD trillion per annum (i.e., about 80% more funding combined with the G20 commitment) until 2050, it could be useful in increasing clean energy initiatives and projects aimed at keeping global warming within the desired threshold.

### *2.6.2 Proximity to Reaching the 1.5 – 2.0 °C Scenario*

Ecosystem biodiversity, human societies, diversified knowledge, climate change adaptation, mitigation, ecosystem health, and sustainable development are highlighted in the IPCC report [76]. By recognizing these interdependences, the value of various forms of knowledge, and the close links between them, this report reflects the increasing diversity of actors engaged in climate action. In a recent 6th Assessment Synthesis Report [51] released this year, the Intergovernmental Panel on Climate Change (IPCC) delivered a gloomy warning that left little space for dispute about the essential significance of taking rapid action and noted that it might be possible to limit the global temperature rise below the 2 °C scenario if there is success in reducing greenhouse gas emissions this decade. Within this time frame, only a dramatic increase in renewable energy and efficiency measures is possible [101]. IRENA's Director-General Francesco La Camera said, "The stakes could not be higher. The global energy system's profound and systemic transformation must occur in under 30 years, underscoring the need for a new approach to accelerate the energy transition". Finding ways to reduce the use of fossil fuels is seen as very important, but the current path of reduction is not enough to make the change to an energy system that works with fully or majorly green sources.

### *2.6.3 Response to the 1.5°C Scenario Issues—Recent Policies of the top $CO_2$ Emitters*

As a result of the 1.5 – 2.0°C scenario issues raised by the IPCC, a few countries have gradually reviewed their existing energy policies to reflect this reality. Table 2.5 summarizes the progress made by the countries categorized as the top $CO_2$ emitters by energy. Europe is included in the list because of its observable large contributions towards the global transition to clean energy. It is important to note that some other countries still derive their measures from previously existing policies.

**Table 2.5.** Recent clean energy policies and NDCs of top $CO_2$ emitters (globally and in Africa) (2020–2023).

| Country/ Region | Summary of Energy-Related Policies for Climate Commitments | Addressing 1.5°C Scenario Issues | Ref. |
|---|---|---|---|
| China | Increased RE Target in the National Grid<br>• The 14th five-year plan raises the target for renewable energy to 30 per cent of total electricity consumption by 2025 (18 per cent for non-hydro renewables).<br>Energy Storage/Hydrogen Roadmap Development<br>• 50 GW new added battery energy storage capacity by 2025. | Partial | [57][102] |
| USA | Approval of the Inflation Reduction Act<br>• Per-unit energy and investment tax credits for solar PV and wind energy systems are extended.<br>• Battery storage and zero-emission nuclear power can qualify for an investment tax credit.<br>• Investment in sustainable energy infrastructure and technology production.<br>Energy Storage/Hydrogen Roadmap Development<br>• 20.8 GW of battery storage by 2025, in addition to the 7.8 GW capacity at present. | Partial | [57][103] |
| India | Expansion of the Production-Linked Incentive (PLI) Scheme<br>• 40 GWh of capacity to produce batteries.<br>• Addition of 50 GWh of capacity to produce solar photovoltaic cells in the next three years.<br>• Reduction of 50 Mtons annual emissions of $CO_2$ by 2030.<br>Hydrogen Roadmap Development | Partial | [57][104] |

| | | | |
|---|---|---|---|
| | • 125GW Capacity of RE for green hydrogen by 2030. | | |
| Europe | Commitment to Increasing Offshore Wind Capacity<br>• Nine EU member states have pledged more than 120 GW of offshore wind capacity installation by 2030 and more than 300 GW by 2050.<br>Announcements by the European Commission—REPowerEU Plan, Net-Zero Industry Act Proposal, and other Potential Reforms<br>• The European Union has proposed a few changes, including a faster permitting process.<br>• An increase in the EU's 2030 renewables target to 45% by 2030 (total energy matrix, not just power).<br>• An increase of around EUR 225 billion in loans for grids.<br>Hydrogen Roadmap Development | Partial | [57][105] |
| Japan | • Reduction of Annual Emissions of $CO_2$ by 46% in 2030 from the 2013 levels.<br>Planned Lifetime Extension of Nuclear Power Plants<br>• The Japanese government is investigating the potential for extending the 60-year lifespan of nuclear power plants.<br>Hydrogen Roadmap Development | Partial | [57] |
| Iran | - | None | |
| Canada | • Reduction of annual emissions of $CO_2$ by 40–45% in 2030 below the 2005 levels and net-zero by 2050.<br>• Phasing out ozone-depleting substances included in the Montreal Protocol.<br>• Adoption of the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) strategically aimed at reducing 2020 emissions by 347 Mt lower than 2015 projections and 36% below the 2005 levels.<br>Hydrogen Roadmap Development | Partial | [106] |
| South Korea | Planned Production Capacity Reduction of Coal-fired Plants and Expansion of Nuclear Power Plants<br>• Energy consumption from coal was cut by 15%.<br>• From the current 10% share in 2021, renewables are expected to rise to 31% and nuclear power to 35% by 2036. | Partial | [57] |
| Indonesia and Southeast Asia | Indonesia-Introduction of Just Energy Transition Investment Plan (JETIP)<br>• Achieve net-zero emissions in the electricity sector by 2050; increase the share of renewable energy in power generation to at least 34% by 2030; hasten the shutdown of coal-fired power plants.<br>• Initial funding of USD 20 billion.<br>Southeast Asia | Partial | [57] |

|  |  |  |  |
|---|---|---|---|
|  | • From roughly 20% in 2021 to 35% in 2030 (and 50% in 2040), the Philippines has set ambitious targets for renewable electricity generation.<br>• Under Thailand’s new policy for renewable electricity procurement, the country’s distribution companies are now required to pay feed-in tariffs and meet new capacity objectives (another 5 GW of biogas, solar, wind, and solar with storage). |  |  |
| Saudi Arabia | - | None |  |
| South Africa | Introduction of Just Energy Transition Investment Plan (JETIP)<br>• Increasing renewable energy projects between 2023 and 2027, aimed at achieving between 350–420 MtCO$_{2\text{-eq}}$ by 2030.<br>• Considering how best to utilize and allocate the USD 8.5 billion on offer from the International Partner Group (IPG), made up of the United Kingdom, France, the United States, and the EU.<br>• Approximately 2%, 8%, and 90% of IPG funding was allocated to electricity, new EVs, and green H$_2$ projects, respectively. However, the funding available can only reach 44% of the national financial target.<br>• Reduction and complete phase-out of all coal-fired power plants by 2034. | Partial | [107] |
| Egypt | • Set targets to reduce GHG emissions in sectors (i.e., electricity, oil/gas, and transport) that contributed 43% of Egypt’s total national emissions in 2015.<br>• Reduction targets of 37%, 65%, and 7% in electricity, oil/gas, and transport, respectively | Partial | [108] |
| Algeria | - | None |  |
| Nigeria | Introduction of Energy Transition Plan (ETP)<br>• Set targets to generate 30GW of electricity from renewables and reach net-zero carbon neutrality in sectors that contribute 65% of the total national emissions by 2062.<br>• There is no clear investment commitment except the target for investors. | Partial | [109] |
| Libya | - | None |  |
| Morocco | • A target GHG emission reduction of 45.5% by 2030, including an unconditional target of 18.3%.<br>• The reduction objective is compared to the reference scenario, representing emissions under a business-as-usual (BAU) path. The mitigation scenario includes 34 unconditional and 27 conditional initiatives regarding international finance. | Partial | [110] |

NDC - nationally determined contribution is a form of GHG emission reduction commitment made by governments under Article 4(2) of the Paris Agreement [48].

As a result of the 1.5–2.0 °C scenario issues raised by the IPCC, a few countries have gradually reviewed their existing energy policies to reflect this reality. Table 5 summarizes the progress made by the countries categorized as the top $CO_2$ emitters. Europe is included in the list because of its observable large contributions towards the global transition to clean energy. It is important to note that some other countries still derive their measures from previous policies.

It can be observed from Table 2.5 that not all the top $CO_2$ global emitters have presented an updated plan to address climate change issues. In contrast, most of the emission reduction targets have only partially addressed the 1.5 – 2.0 °C scenario, as other factors and emissions from non-energy industries are hardly mentioned in the NDC commitments pledges found in the UNFCCC registry [91], [92].

It is problematic that all the current policy plans and ongoing implementations may not achieve the UN SDG target of the world becoming a sustainable, developed society by 2030 while ensuring that the suitable global warming threshold is maintained.

Therefore, and as has been previously discussed in this work, urgent but rational decisions and massive investment structures that match stated intentions with actions are required if this is to be achieved and spare the global population from the menace of climate change.

### *2.6.4 Increase in 100% Renewable Energy System Possibilities and SED*

There have been changes to the energy system, the economy, and the environment as the global energy system is transitioning towards renewable energy exclusively. The use of varying renewable energy sources, including solar, wind, hydro, geothermal, and biomass, is a great part of this shift, and a transition to 100% renewable energy would have positive effects on the environment, energy security, the economy, and the creation of jobs [111], [112], [113]. Table 2.6 shows the progress from 2018 to 2022 regarding the increasing penetration of RE in the national/regional energy mix of the G20 and the resulting contribution to reducing $CO_2$ emissions.

**Table 2.6.** RE penetration and $CO_2$ emissions reduction progress for G20 countries.

| **S/N** | **Country (G20)** | **Emission ($CO_2$) in 2018 Mt** | **Emission ($CO_2$) in 2019 Mt** | **Emission ($CO_2$) in 2020 Mt** | **Emission ($CO_2$) in 2021 Mt** | **Emission ($CO_2$) in 2022 Mt** | **RE in National Mix (%) in 2018** | **RE in National Mix (%) in 2019** | **RE in National Mix (%) in 2020** | **RE in National Mix (%) in 2021** | **RE in National Mix (%) in 2022** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | United States | 5380 | 5260 | 4720 | ***4903*** | ***4970*** | 17.45 | 18.29 | 20.32 | 20.74 | 22.52 |
| 2 | India | 2600 | ***2630*** | 2450 | ***2701*** | ***-*** | 16.69 | 18.69 | 20.21 | ***19.38*** | 20.48 |
| 3 | Germany | 754.41 | 707.15 | 639.38 | 674.75 | 655.5 | 35.1 | 40.09 | 44.33 | 39.7 | 42.95 |
| 4 | China | 10350 | ***10,740*** | ***10,960*** | ***11,470*** | 11447 | 25.77 | 27 | 28.25 | 28.91 | 30.67 |
| 5 | Canada | 584.37 | 584.71 | 534.86 | ***545.63*** | - | 67.37 | ***67.17*** | 68.78 | ***68.17*** | 69.74 |
| 6 | United Kingdom | 379.73 | 364.75 | 326.26 | ***346.77*** | 331.5 | 33.29 | 37.46 | 42.86 | ***39.78*** | 41.45 |
| 7 | France | 322.53 | 316.39 | 280.03 | 274.4 | 269.7 | 19.73 | 20.01 | 23.76 | 22.23 | 24.54 |
| 8 | Italy | 349.01 | 339.23 | 302.28 | ***328.69*** | 317.7 | 39.81 | ***39.76*** | 42.04 | 40.62 | ***36.44*** |
| 9 | Japan | 1140 | 1110 | 1040 | ***1170*** | - | 18.14 | 19.42 | 21.32 | 22.61 | 23.63 |
| 10 | Turkey | 422.57 | 401.72 | ***413.43*** | ***446.2*** | - | 32.18 | 43.68 | ***42.02*** | ***35.56*** | 41.97 |
| 11 | Mexico | 475.27 | 472.19 | 391.71 | 407.21 | - | 17.7 | 18.55 | 21.26 | 23.94 | ***22.94*** |
| 12 | Australia | 416.28 | ***416.36*** | 399.92 | 391.19 | - | 17.15 | 21.38 | 25.05 | 29.13 | 32.3 |
| 13 | Indonesia | 603.66 | ***659.44*** | 609.79 | ***619.28*** | - | 17.05 | ***16.26*** | 18.13 | 18.17 | 19.62 |
| 14 | Saudi Arabia | 626.19 | 656.48 | 661.19 | ***672.38*** | - | 0.05 | 0.21 | 0.06 | 0.23 | 0.21 |
| 15 | Korea, DPR | 670.17 | 646.1 | 597.63 | ***616.08*** | - | 5.23 | 5.76 | 6.13 | 7.77 | 9.21 |
| 16 | Russia | 1700 | 1690 | 1620 | ***1760*** | - | 18.42 | 18.55 | 20.74 | ***19.96*** | ***18.36*** |
| 17 | Brazil | 477.1 | 475.1 | 442.31 | ***488.88*** | - | 82.92 | ***82.85*** | 84.64 | ***76.77*** | 86.94 |
| 18 | Argentina | 180.6 | 178.51 | 169.26 | ***186.45*** | - | 25.02 | 26.01 | 26.71 | ***25.35*** | 31.43 |
| 19 | South Africa | 435.24 | ***466.92*** | 435.83 | ***435.93*** | - | 5.16 | 5.36 | 5.78 | 7.56 | 9.09 |
| 20 | European Union | 3050 | 2910 | 2620 | ***2740*** | 2730 | 32.29 | 34 | 38.45 | ***37.34*** | 38.36 |

Data for RE% and $CO_2$ emissions were extracted [113] [114], respectively. The text in italics and bolded indicates a decline in the progression of either increase in $CO_2$ emissions or RE% reduction from the previous year, respectively.

Table 2.6 presents the progression of either $CO_2$ emissions reduction or RE% increment for the G20 countries. For some years, there has been a retrogression in either the $CO_2$ emissions reduction or RE% increment, while only France and Germany have maintained consistent growth in both cases across 2018–2022. Emissions, particularly between 2020 and 2022, increased significantly across all the G20 countries except France, Germany, Indonesia, and Australia. The general increase is due to the re-opening of industries post-COVID-19. The year 2022 showed positive progress in the data available for the few countries that are the greatest emitters.

According to the IEA $CO_2$ emissions report of 2022 in [114], trends in energy-related $CO_2$ emissions were observed as follows:

- Energy-related global $CO_2$ emissions climbed by 0.9%, or 321 Mt, hitting a new high of more than 36.8 Gt.
- Difficulties in 2022 had an impact on the rise in emissions. Overall, 60 Mt $CO_2$ of the 321 Mt $CO_2$ increase is attributable to the requirement for cooling and heating during severe weather, while another 55 Mt $CO_2$ is associated with the shutdown of nuclear power plants.
- Energy combustion emissions increased by 423 Mt, while emissions from industrial processes decreased by 102 Mt.
- The increased usage of sustainable energy technologies, including heat pumps, electric vehicles, and renewable energy sources, helped prevent an extra 550 Mt of $CO_2$ emissions.
- Oil emissions climbed by 2.5%, or 268 Mt, compared to coal emissions, to reach 11.2 Gt.
- Despite the switch from petrol to coal in many countries, the global growth in emissions was less than expected in a year marked by energy price shocks, rising inflation, and disruptions to conventional fuel trading patterns.
- Due to supply issues made worse by Russia's invasion of Ukraine, natural gas emissions declined by 1.6%, or 118 Mt. The highest decrease in petrol emissions (-13.5 %) was seen in Europe. Significant drops (−1.8%) were also noted in the Asia-Pacific region.
- A significant growth in renewable energy sources significantly decreased the revival in coal power emissions. Last year, renewable energy sources generated 90% of the additional electricity used worldwide. A new annual record was set by an increase in wind and solar PV generation of almost 275 TWh each.
- Except for China, emissions from emerging markets and developing economies in Asia increased by 4.2% or 206 Mt $CO_2$ in 2022, outpacing emissions from all other regions. The region's emissions increased by more than half because of coal-fired power generation.
- The combined production of wind and solar PV electricity surpassed gas or nuclear power for the first time.

Figure 2.9 shows 30 countries whose primary energy is at least 50% renewable energy. Nations such as Nepal, Iceland, Bhutan, and Albania have successfully attained a complete reliance on renewable energy sources, with consumption rates approaching 100%. In Ethiopia, DR Congo, Norway, Costa Rica, Namibia, Kenya, and Uganda, energy generation consists of between 70 and 99% RE. However, the measure of the population with electricity access is not 100%, as depicted in Figure 2.9.

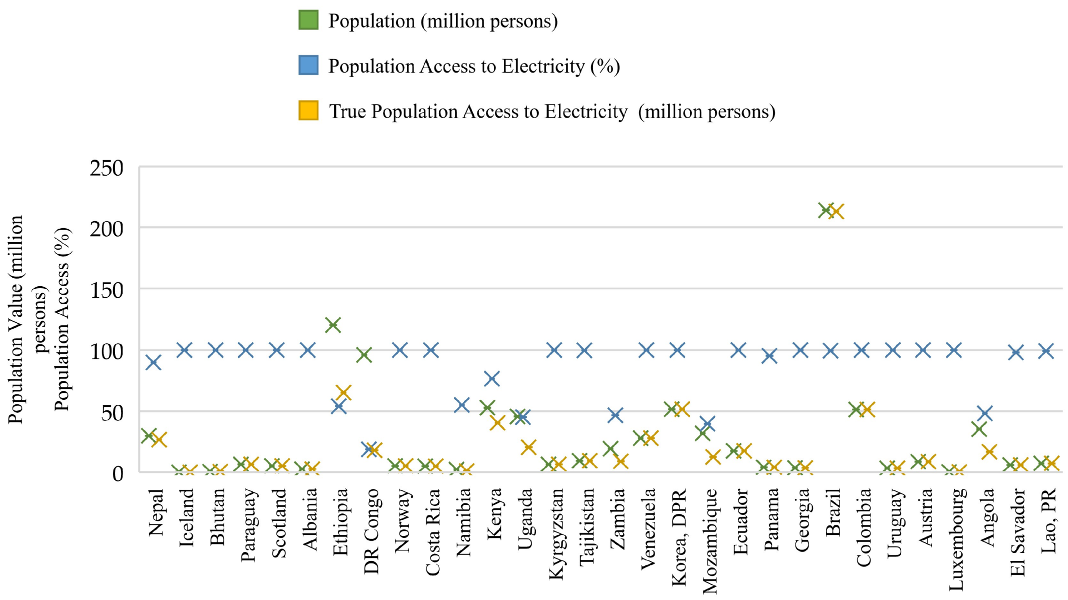


**Figure 2.9.** Population with true access to electricity in countries with high RE (70% or higher). Data from [90], [115].

As can be noted from Figure 2.9, even though electricity generation is nearly 100% RE in the countries presented, not all the population has access to electricity. Of the 30 near 100% RE countries, with a total population of 0.865 billion, 20% have no electricity yet, mainly in developing countries. From Figure 2.9, almost all the African countries in the list have a very large proportion of the population with no electricity access. Ethiopia, DR Congo, Kenya, and Angola, with populations of 120.3, 95.9, 53, and 35.6 million, respectively, have populations with electricity access of only 54.2, 19, 76.5, and 48.2%. In comparison, the other countries with almost 100% electricity access, apart from Brazil, have lower populations compared with the near 100% RE African counterparts.

Implementing a completely renewable energy system has the potential to significantly impact the communities in these countries that currently do not have access to electricity [116]. This impact can have positive and negative consequences depending on many factors and circumstances. These are discussed further and summarized in Table 2.7.

The emphasis on prioritizing power access to remote and underserved areas may be heightened to complete a transition to renewable energy sources. The decentralization of renewable energy sources, such as solar and wind, enables electricity distribution to previously inaccessible areas hindered by the connectivity constraints of traditional centralized power grids. Renewable energy technologies are often deemed appropriate for deployment in smaller-scale systems, such as microgrids or off-grid installations. These systems have the potential to be deployed in isolated areas that have limited connection to larger power grids, therefore facilitating the utilization of energy resources without necessitating extensive infrastructure. The deployment of renewable energy infrastructure possesses the capacity to create job prospects and stimulate economic development within the community. The possibility to improve living circumstances exists through energy distribution to populations that previously lacked access. The preliminary costs of establishing renewable energy infrastructure, such as deploying photovoltaic panels and wind turbines, can be significant. The possible hurdle to the adoption of these technologies by poor groups may be mitigated with substantial external help.

Some geographical regions may have restrictions in terms of the necessary infrastructure and technical expertise needed for the effective deployment of renewable energy solutions. To ensure successful implementation, training and capacity-building programs must be offered to address the intermittency and reliability of various renewable energy sources, including solar and wind. Providing reliable electricity can pose challenges, particularly in regions where a consistent power supply is vital for critical sectors such as healthcare and education. The integration of renewable energy sources relies heavily on energy storage, as it facilitates electricity supply during periods characterized by limited solar irradiation or wind activity. Deploying reliable energy storage systems in remote areas may pose diverse obstacles and substantial financial consequences. When transitioning to renewable energy, it is imperative to consider the influence of cultural and social issues because adopting renewable energy may necessitate adjustments in local lifestyles, energy consumption patterns, and even traditional practices. Achieving a harmonious equilibrium between these modifications and preserving cultural values is necessary. Installing large-scale renewable energy projects gives rise to environmental and land use concerns, which have the potential to result in substantial consequences for local ecosystems and land use. Including thorough environmental assessments and active involvement of local communities are essential components within the decision-making framework.

**Table 2.7.** Possible impacts of increasing energy accessibility in developing countries. Source: author's elaboration.

| Impact | Highlights | |
|---|---|---|
| Positive | 1. | Ease of facilitation in achieving the 100% RE vision. |
| | 2. | Substitution of high infrastructural cost using microgrid powered by RE. |
| | 3. | Jobs and economic development. |
| Negative | 1. | Human capacity and technical challenges with deployment. |
| | 2. | Energy storage challenges to manage intermittency and reliability in supply. |
| | 3. | Environmental impact from land and water uses for installation and operations. |
| | 4. | Energy affordability issues with the high cost of RE. |

In summary, the potential ramifications of implementing a comprehensive renewable energy initiative for populations lacking access to electricity depend on several factors, such as the selected approach, technological advancements, government support, financial capabilities, and community involvement.

It is crucial to recognize and address impediments while tailoring solutions to accommodate the unique needs mentioned in this section and the conditions of certain geographical areas, which have become rising issues in SED. The next section discusses selected emerging challenges and directions of SED.

## 2.7 Emerging Issues and Directions in SED

### *2.7.1 Energy War*

The ongoing geopolitical tensions between Russia and Ukraine have significantly affected the European energy sector. Meanwhile, other similar but diverse issues of war that have impeded energy development progress have been prevalent in other parts of the world, for instance, in African countries, particularly in the Sahel and sub-Saharan region of the continent. These tensions have had implications for climate change dynamics and global efforts to limit global warming to 1.5 °C. The ongoing conflict has significantly disrupted supply chains and heightened uncertainty within the energy industry. As a result, the transportation of natural gas and energy prices, for instance, in Europe, have been notably impacted. The ongoing conflict has resulted in a notable transition towards carbon-intensive energy sources, with a particular emphasis on coal. This shift poses a significant challenge to limiting global warming to the critical threshold of 1.5 °C. The global community faces intricate challenges posed by climate change and its geopolitical ramifications, underscoring the significance of international collaboration in mitigating the adverse impacts of conflict on energy security and climate change objectives.

The global imperative for energy security and the imperative to transition towards sustainable energy sources have emerged as crucial priorities on a global scale. In the face of global climate change and the imperative for a transition to clean energy, it is evident that international cooperation in clean energy financing plays a crucial role in averting potential conflicts over energy resources. The Russia–Ukraine via Europe energy conflict exemplifies the crucial need for collaborative endeavours to safeguard energy security, promote energy source diversification, and mitigate reliance on fossil fuels. In addition to the need for international collaboration, the energy security issue has also necessitated the massive adoption of storage technologies that can serve as an alternative measure in fostering energy independence. Presently, the need cannot be overemphasized as the technology must gain maturity.

The next section presents the different energy storage pathways and concludes with a discussion of the progress in hydrogen policy planning in the selected top GHG emitters by energy.

### *2.7.2 Energy Storage*

Using energy storage technologies is becoming more prevalent to decouple the timing of energy output from its consumption, whether in the form of electricity or heat. Chemical methodologies such as lead-acid and lithium-ion batteries are widely employed, whereas pumped hydro storage represents a mechanical approach. Molten salts are a highly efficient means of storing thermal energy in concentrating on solar power systems, allowing for a more compact storage solution. The declining costs associated with renewable energy sources such as solar and wind are expected to contribute to an increased proportion of these sources within the broader energy mix. The growing prevalence of intermittent renewable energy sources necessitates the development of power grid facilities capable of accommodating and responding to fluctuating conditions. The advancement of electricity storage systems, with a specific focus on battery and hydrogen technology, has a pivotal impact on the adaptability of the electrical grid. A comparison of energy storage technologies' performance based on different metrics is presented in Table 2.8, and the rating is summarized in Figure 11. These prominent energy storage technologies are five, namely chemical energy storage, thermal energy storage, electromagnetic energy storage, mechanical energy storage, and peak cutting and trough filling technology.

**Table 2.8.** Performances of energy storage pathways. Source: authors' elaboration.

| **Performance Indices** | **Chemical** | **Thermal** | **Electromagnetic** | **Mechanical** | **Peak Cutting and Trough Filling** |
|---|---|---|---|---|---|
| Life span | 1.14 years $^{4}$ | 30 years $^{2}$ | 30 years $^{2}$ | 30–60 years $^{1}$ | 2 years $^{3}$ |
| Storage cycle | 365 days $^{1}$ | 7–28 days $^{3}$ | 1–6 days $^{4}$ | 7–30 days $^{2}$ | 1–6 days $^{4}$ |
| Response time | Minutes $^{3}$ | Weeks to hours $^{4}$ | Days long $^{5}$ | Seconds to minutes $^{2}$ | Hundred milliseconds$^{1}$ |
| Storage capacity | MW–GW $^{1}$ | MW $^{2}$ | kW–MW $^{2}$ | GW $^{1}$ | kW–MW $^{2}$ |
| Storage efficiency (range) | 0.3–0.8 $^{5}$ | 0.5–0.9 $^{3}$ | 0.8–0.98 $^{1}$ | 0.7–0.85 $^{4}$ | 0.6–0.95 $^{2}$ |
| Cost | USD (2801–7002)/kW $^{3}$ | USD (280–420)/kW $^{2}$ | - $^{4\text{ or }5}$ | USD (140–840)/kW $^{1}$ | USD (281–420)/kW $^{2}$ |
| Energy density | Very high $^{1}$ | Moderate $^{3}$ | Low $^{4}$ | Low $^{4}$ | High $^{2}$ |
| Environmental Impact | | | | | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Resources for generation | Existing energy resources (both fossil and RE), depending on the production method [1] | Heat [2] | Electromagnetic field [2] | Mechanical work [2] | Cutting and trough filling [2] |

Data extracted from [117]. Note—1, 2, 3, 4, and 5 are rankings used to show the best performer per indices, with 1 being the best, followed by 2, and so on, with 5 being the worst. These rankings are compared in Figure 2.10.

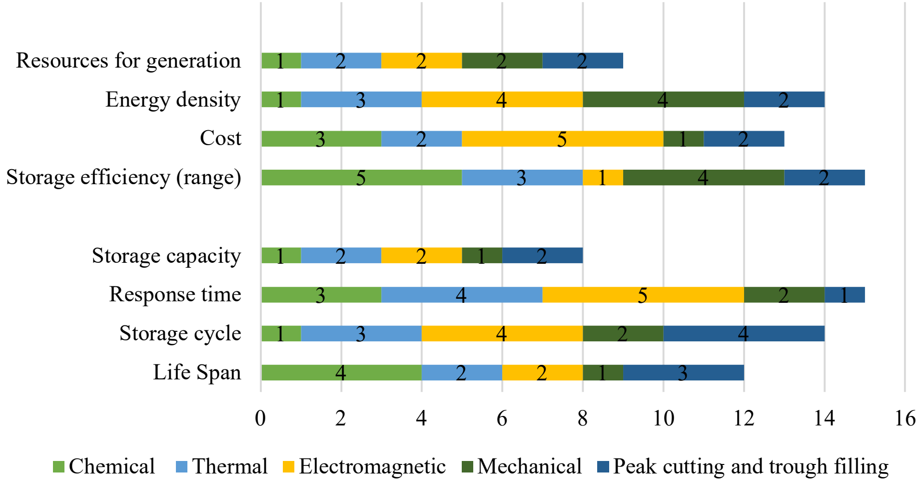


**Figure 2.10.** Performance rating of energy storage pathways. Source: author's elaboration.

From Figure 11, chemical energy storage (CES) offers the most promising energy storage pathway as it is the only storage pathway coming first in four out of the eight performance ratings. The storage cycle could last for a calendar year in the event of a national energy crisis, which appears to be one of the reasons it is commonly the major energy storage that has gained most countries' national policy attraction, as noted in Table 2.5. However, the major drawbacks of CES are the cost of producing a kg worth of hydrogen, which requires between 33 and 55 kWh of electricity (with a high cost of USD 2801–7002/kW), and its low storage efficiency. It makes other energy storage options viable even though growing innovative approaches are working toward reducing the hydrogen production cost per kg. Also worth noting is that the hydrogen cost per kWh depends on the production technology and the type of resources used as the feedstock in hydrogen production.

Hydrogen, being a form of CES, has emerged as the most viable energy delivery mechanism for the future as a well-known carbon-free or less gaseous fuel as it is a desired fuel for several power sources, including internal combustion engines, gas turbines, and fuel cells, due to its good mass-basis calorific value, absence of carbon atoms [118], and derivability from existing energy systems and processes. Hydrogen production is divided into three technological groups: thermochemical, electrochemical, and biological. Most hydrogen energy production systems employ cradle/gate-to-gate borders, while most hydrogen transportation systems use cradle/gate-to-grave barriers [119]. The article by N. H. Afgan et al. in [120] discussed the potential for multi-criteria evaluation of hydrogen systems based on performance, environment, market, and social aspects. H. Zhao et al. [121] analyzed and proposed a resilience assessment strategy and improvement-tracking mechanism to integrate hydrogen energy efficiently and in times of emergency. Case studies have been conducted to demonstrate the viability of the proposed approach [63]. Multi-criteria evaluation of hydrogen infrastructure considers performance, environmental factors, and market variables, and the Sustainability General Index (SGI) ranking is more helpful for decision-making than relying on a single indicator [122]

In IRENA's report in [123], using a five-step process, a more detailed methodology for assessing the best energy storage options (of which hydrogen and other forms of energy storage are included) is presented. The first step is determining which energy storage services make variable RE integration easier, and the second is matching the appropriate storage technology with those services. Third, the value of electricity storage systems is compared to other flexibility mechanisms. The fourth stage is to perform revenue modelling by simulating stacking and storing operations, while the last is to assess the feasibility of the storage project, valuing a system based on its expected return on investment. Overall, the merits and demerits of all energy storage technologies, alongside other criteria, are presented in Table 2.9.

**Table 2.9.** Comparison of energy storage pathways/technologies.

| Technology/ Pathway | Storage Application | Applicable Scenarios | Merits | Demerits | Maturity of Technology |
|---|---|---|---|---|---|
| Chemical | Hydrogen<br>Natural gas | Large-scale, long-cycle energy storage | Long storage cycle<br>High storage energy volume | High infrastructure requirements<br>Sluggish response<br>Low efficiency but high cost | Low |
| Thermal | Molten salt | 7–28 days | High thermal storage volume | Limited applicable scenarios | Moderate |
| Electromagnetic | Supercapacitor<br>Superconducting | Peak load regulation, direct use of thermal energy | Long life span<br>Fast response | Seconds to minutes | Low |
| Mechanical | Flywheel<br>Compressed air<br>Hydro-pump | Large-scale energy storage by peak | Very high technological maturity<br>Longer life span | High infrastructure requirements<br>Sluggish response | Very high |

| | | | | | |
|---|---|---|---|---|---|
| | | cutting and trough filling | Low cost of operation<br>Large energy and power capacity | | |
| Peak cutting and trough filling | Battery | Peak load and frequency regulation | High technological maturity<br>High flexibility in construction/installation<br>Fast response | Intermittent problem of heating<br>High infrastructure cost requirements | High |

Information and data extracted from [117].

Even in the absence of many new governmental initiatives on energy storage, existing patterns of technical innovation and diffusion are continuously on the rise, as in the case of Hydrogen. P. Saha et al. [124] investigated the different production processes and examined the economic and environmental effects of three different hydrogen categories based on the resources used as feedstock (fossil fuel—grey, blue—and fully renewable energy—green). In the current paradigm, the emphasis is more on green hydrogen generation technology at the least possible cost because of the net-zero friendliness of green hydrogen compared with the blue and grey types, which are fossil-based. In an editorial by F. Calise et al. in [125], recent advances in green hydrogen technology were reviewed. Such advances include the hydrogenation of captured $CO_2$ in [126], green hydrogen from multi-renewable energy systems, as seen, for instance, with hydrogen from wind + geothermal in [127], wind + solar + electrolyzers + fuel cells in [128], and solar + electrolyzer + absorption chiller + electric +thermal energy storage in [129].

In addition to the advances towards the least-cost path for green hydrogen generation, legal reforms and political will are paramount to supporting the infrastructural expansion of green hydrogen in the global energy mix. Therefore, given the viability of the massive adoption of the hydrogen energy stream as a more promising option, Table 2.5 indicates the countries with a hydrogen roadmap. In addition, recent years have seen a boom in the industry’s hydrogen production, which has attracted much attention. While established companies drove much of the sector’s rapid expansion in the past, the commercial landscape today is more open and welcoming to new entrants in the hydrogen industry.

### *2.7.3 Decarbonization Strategies for SED in Power and Other Sectors*

Many obstacles must be overcome to reach a sustainable, energy-developed society globally. Alongside moving clean energy financing towards 100% and the emerging issues of energy war and storage discussed previously, other key constraints include less political will, regulatory opposition, and high initial costs [112], [130], [131], among a host of others.

Advocacy for a forward-thinking strategy, strong policies, widespread education, and the participation of both the public and private sectors is pertinent. Due to differences in energy resources capacity, geographical challenges, and other challenges, addressing the issues/constraints highlighted in Table 2.10 may require a global and integrated perspective and international/regional collaboration for the sustainable development of the energy system that powers a sustainable future.

**Table 2.10.** Issues and constraints surrounding SED decarbonization strategies. Source: authors' elaboration.

| Category | Issues and Constraints | Related SED Themes (from Tables 2 and 3) |
|---|---|---|
| Institution and Politics | • Challenging support policies for increasing penetration of RE. [5,7]<br>• Less government financing and subsidy. [10]<br>• Energy wars. [1]<br>• Rise in the disintegration of international treaties (uprise of the BRICS group versus G7, G20). [1] | 5, 7, 10, 1 |
| Technology Systems | • Challenges in maintaining grid stability because of varying RE in the existing conventional national grid. [1,6]<br>• The initial cost of decentralized energy generation and storage. [8,10]<br>• Challenging energy storage trade-offs (less storage cycle, high levelized storage cost). [7,10]<br>• Challenges with high energy requirements for existing direct carbon capture and sequestration technologies. [6,7,8,10] | 6, 1, 8, 10, 7 |
| Climate Change Concerns | • Deforestation issues in the event of sudden utilization of forest resources for the energy transition. [8]<br>• Material and resource requirements for the energy transition (for instance, there may be a possible overshoot of natural earth resources for renewable and storage applications system development in the event of immediate transition into full 100% RE). [8,10]<br>• Heat waves—intermittent cooling and heating needs of the population. [2,4,8] | 8, 10, 2, 4 |
| Public Opinion | • Energy markets (dwindling public trust for complete transition into 100% RE, less affordability, regional energy trade competitions). [3,5,10]<br>• Adaptation issues with changing job and skill requirements for the new energy paradigm. [9]<br>• Rising demand for energy accessibility in developing countries. [3,9,10] | 3, 5, 10, 9 |

The numbers 1 to 10 are nomenclatures used to show the commonality and similarities with each sub-theme in Tables 2 and 3.

The constraints listed in Table 2.10 can all be categorized under the 10 themes of SED that this study earlier identified in Section 2.3. Aligning these interrelated constraints with each of the themes of SED and inclusion in responsive policy regulatory development of countries could help significantly in tackling these issues and the challenges of climate change and SED. Apart from the utilization of promising energy storage solutions, energy efficiency measures, high carbon pricing, introduction of clean electricity standards, fossil fuel taxing, renewables energy subsidy, accelerated retirement of non-renewable energy plants, limiting sales of fossil-fuel-driven transport system, and other circular economy concepts to address the SED decarbonization constraints, the power sector and other sectors are exploring several potential strategies. These decarbonization strategies are depicted in Table 2.11.

**Table 2.11.** Selected emerging decarbonization strategies for power and other sectors. Source: authors' elaboration.

| Sector | Emerging Energy-Related Decarbonization Strategies | Merits | Demerits | Technology Maturity Level | Ref. |
|---|---|---|---|---|---|
| Power | 1. Bioenergy with the capture of resulting $CO_2$ emissions.<br>2. Capture of $CO_2$ from fossil fuel emissions.<br>3. $CO_2$ methanation-energy resource (methane) recovery using the captured $CO_2$ as a feedstock.<br>4. Green hydrogen production and storage<br>5. Composites and materials hybridization for solar cell efficiency optimization. | 1. Reduced $CO_2$ deposition in the atmosphere.<br>2. Alternative energy generation.<br>3. Improved generation efficiency. | 1. High operational cost.<br>2. High energy requirement.<br>3. $CO_2$ storage constraint and durability of the reservoir.<br>4. Many hybridizations of materials as a composite are still at trial/experimental stages of development. | low | [125], [132], [133], [134], [135] |
| Industrial processes | 1. Net-zero carbon and energy-intensive cement production using basalt and other calcium oxides (replacing limestone).<br>2. Industrial symbiosis (the waste in one industry becomes a resource for another).<br>3. Nanotechnology and Composite materials and intelligent manufacturing techniques. | 1. Possibility of replacing 98% of cement production from limestones with $CO_2$ emission avoidance.<br>2. Waste reduction with energy savings and $CO_2$ emission avoidance.<br>3. Increased power conversion efficiencies | 1. Uncertain solutions (i.e., limestone replacement not yet tested at industrial scale).<br>2. Many hybridizations of materials as composites are still in the trial/experimental stages of development. | low | [136], [137][138] |
| Transport | 1. Use of vehicle-to-grid (V2G/G2V) for electric vehicle (EV) charging and energy trade. | 1. EVs are eco-friendly during their operational phase.<br>2. Reduced $CO_2$ deposition in the | 1. High initial purchase cost.<br>2. The use of EVs requires grid stability and the right charging mechanisms. | low | [139], [140] |

| | | | | | |
|---|---|---|---|---|---|
| | 2. Smart mobilities such as vehicle-to-vehicle (V2V) and autonomous vehicles.<br>3. Battery management system and solid-state batteries for EVs.<br>4. Sustainable aviation fuels (SAF) for commercial purposes are made from $CO_2$ via RE plus water synthesis.<br>5. Conversion of petrol/diesel to compressed natural gas (CNG) engines. | atmosphere with CNG use.<br>3. Reduced carbon intensity requirement and performance optimization mid-term trade-off for V2G, V2V, EV, SAF, and CNG. | 3. EV battery materials resources' availability is not location specific.<br>4. High conversion cost.<br>5. High safety handling requirements for CNG vehicles. | | |
| Building | *Innovative Active Cooling/Heating*<br>1. Use of heat pump, solar, and geothermal heating.<br>2. Alternative cooling technologies, such as vortex tubes.<br>3. Decentralized district heating and cooling using microgrids.<br>4. Intelligent and user-responsive cooling/heating using ML/AI techniques.<br>*Passive Cooling*<br>5. Efficient building envelope designs and retrofitting.<br>6. Phase-change materials for cooling and heat storage. | 1. Reduced $CO_2$ deposition in the atmosphere.<br>2. Alternative cooling and heating during intermittent seasonal demands. | 1. High operational energy requirement for some alternative cooling/heating techniques.<br>2. High initial cost of installation and commissioning. | low | [141], [142] |

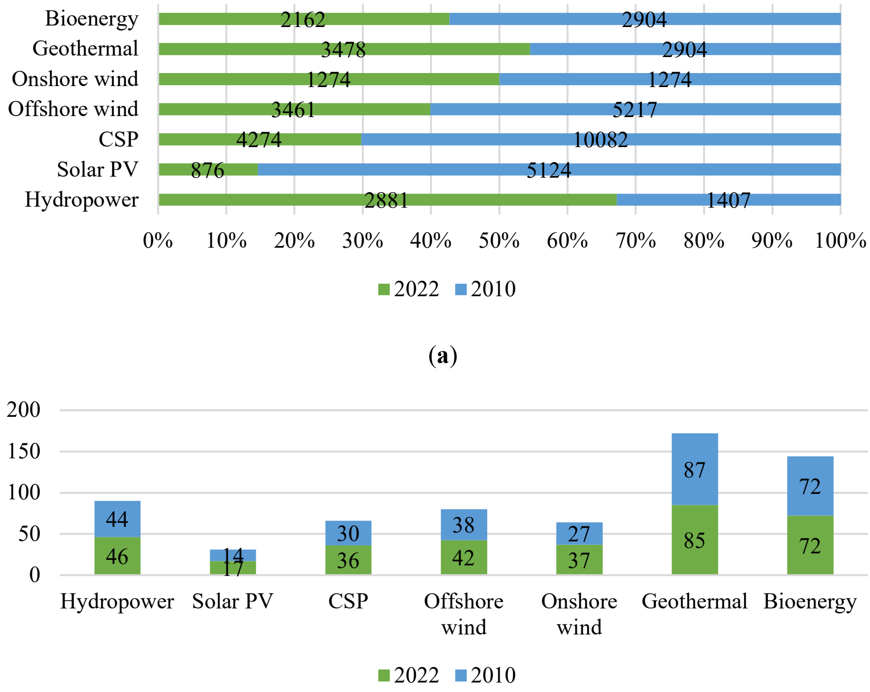
ML/AI—machine learning/artificial intelligence.

The next section presents a brief on energy innovation and financing climate change for sustainable development and concludes with laying a foundation for the next chapter of this thesis.

## 2.8 Energy Innovation, Financing, and Sustainable Development

A study on sustainable innovation tried to link financial growth with energy innovation and predicted that by 2030, energy finance could play a 40% essential role in the energy transition paradigm [143]. Proper energy financing is a key component of the framework of the study, which could benefit sustainable energy innovations that further energy development and the Sustainable Development Goals [143]. To assess the benefits of green energy finance (GEF) for green energy technology/innovation (GEI) and carbon efficiency, L. Pang in [144] looked at how it affects both areas. The link between these variables was evaluated using the wavelet-based quantile-on-quantile approach. The results indicated that, in the near to medium term, green energy finance could probably have compound impacts on GEI across various market sizes and conditions. In contrast, in the long run, the bull GEF market might be able to use the positive outcomes, while the bear market might take advantage of the drawbacks. The outcomes vary from short-term to long-term [144]**.**

Because of the connection between innovation and environmental sustainability, many countries have prioritized renewable energy financing and technological innovation to these ends [145][146]. In addition, the emergence of new materials, increased production efficiencies, policy support, and the large benefits of renewables have greatly helped reduce the cost of renewable energy technologies. Examples of these cost reductions between 2010 and 2022 are represented in Figure 2.11 and Table 2.12 for the Levelized Cost of Energy (LCOE) of seven RE technologies.



**(a)**

**(b)**

**Figure 2.11.** Total installed costs and the capacity factor of RE technology. (**a**) Total installed cost of RE (UDS/kW), according to the IRENA report in [147]; (**b**) RE capacity factor, according to the IRENA report in [147].

**Table 2.12.** (LCOE) trends by technology, 2010 and 2022, according to the IRENA report in [147].

| Energy Technology | LCOE (USD/kWh) | LCOE (USD/kWh) | |
|---|---|---|---|
| | 2022 | 2010 | % Change |
| Hydropower | 0.061 | 0.082 | 25.61 decrease |
| Solar PV | 0.049 | 0.445 | 88.98% decrease |
| CSP | 0.118 | 0.380 | 68.95% decrease |

| | | | |
|---|---|---|---|
| Offshore wind | 0.081 | 0.197 | 58.88% decrease |
| Onshore wind | 0.033 | 0.107 | 69.16% decrease |
| Geothermal | 0.056 | 0.053 | 5.666% increase |
| Bioenergy | 0.061 | 0.082 | 25.61% decrease |

The transition to a low-carbon society and sustainable development relies heavily on technological development since technological innovation in energy systems has been shown to minimize carbon emissions [146][148]. Eco-innovations in terms of increased energy-efficient systems contribute to economic growth and reduce environmental damage by decreasing emissions from energy use and promoting better resource utilization [149], [150]. Such possibilities are easier with proper financing systems that support the investment of capital into such research and projects, as has been a consensus among the leadership of nations and international agencies/organizations/forums about energy financing. Recently, global leaders have made it a priority to promote the widespread use of low-carbon, sustainable technologies that are scalable and transferable in both industrialized and developing nations in the bid to meet the COP21 goals [151], [152], [153]. COP21 emphasizes the importance of carbon neutrality and environmental sustainability, and countries must shift to renewable energy, reduce emissions, and adapt to climate change through green investment and technological innovation. The study by K. Zhang et al. in [154] examines 49 countries that issued green bonds between 2007 and 2019, highlighting the connections between pollution, climate change, and renewable energy use and affirming that green finance is an effective strategy for combating global warming and environmental issues. Accelerating green finance growth is crucial for sustainable development, fostering collaboration among sectors such as innovation, renewable energy, environment, and climate [155].

Facilitating green finance is not without challenges; for instance, after the COVID-19 pandemic, the cost of green financing for renewable energy expansion, with private investment being a key factor in reducing greenhouse gas emissions, has increased. Therefore, the need for more private investment to assist green energy funds and encourage investment in clean technology has risen. In addition, only a few industrialized countries with high technological capacity receive most of the private investment in green finance despite its importance for sustainable development. Financing for technology transfer (TT) and supporting stakeholders in the energy sector in developing countries is crucial for the UNFCCC and Kyoto Protocol, enabling faster implementation of environmentally sustainable technologies, policies, and procedures across the different regions of the world.

The work by C. Karakosta et al. in [156] analyzes the benefits and drawbacks of TT implementation and its impact on energy infrastructure. Innovation systems must actively cultivate economic and social capital through multi-stakeholder networks, as natural and social capital are not easily replenished. Power and lack of trust in markets can hinder progress, as seen in monopolistic electrical corporations' attitudes toward distributed energy and intellectual property. With proper financing and technology transfer, developing countries and smaller organizations can develop disruptive technologies due to the importance of domestic institutional frameworks and cultural norms. Factors influencing this green energy private financing and technology transfer/adoption include relative benefit, compatibility, complexity, observability, trialability, and risk. Addressing these factors and familiarity with new opportunities could make smaller-scale breakthroughs in energy technologies and implementations easier.

## 2.9 Energy, Climate Change, and Sustainable Development

The importance of energy in accomplishing the objective of sustainable development has been emphasized ever since it was placed on the international policy agenda [3]. To begin with, international conventions and treaties such as the UN Framework Convention on Climate Change and the Kyoto Protocol [77], [80] have reframed energy development as a tool to reduce emissions of greenhouse gases and combat climate change. Energy problems were not found to be related to any other aspects of progress [71]. A new development paradigm that considers energy development's economic, environmental, and social impacts was mentioned in the IEA report in [2], which had its genesis in the UNDP's 2000 World Energy Assessment (WEA) study. According to the same IEA report, maintaining energy systems within the "carrying capacity of ecosystems" is essential for continuing economic growth and social fairness. The UN 2030 agenda report in [88] underlined the need for reliable, low-cost energy to meet these targets. Over the past three decades, SED has expanded to become an international, all-encompassing policy goal across more than 190 countries that are members of the UNFCCC and signatories to the Paris Agreement [77].

Each country and its energy system have unique difficulties and solutions for SED [71], [157]. The article by P. Nejat et al. in [158] compares the situation of energy use, $CO_2$ emissions, and energy policy around the world using China, the US, India, Russia, Japan, Germany, South Korea, Canada, Iran, and the UK as the benchmark cases since they account for two-thirds of global $CO_2$ emissions. Along with these ten countries, the world's household energy consumption grew by 14% between 2000 and 2011, with most of this rise occurring in developing countries due to urbanization, increasing population growth, and other factors. Currently, traditional biomass makes up 40% of the world's residential energy market, followed by electricity (21%) and natural gas (20%). Strong energy policies, such as energy codes for buildings, subsidies, and energy labels, are necessary to control energy consumption. Nevertheless, because there is no comprehensive, efficient approach, countries such as China, India, and Iran continue to see huge increases in GHG emissions and energy consumption.

Consequently, this has necessitated the drive for massive adoption of renewable energies. To promote the widespread adoption of renewable energy sources in the Gulf Cooperation Council (GCC), the work by Z. Abdmouleh et al. in [159] provided regional decision-makers and international stakeholders with a collection of policy suggestions. A high-level summary of the RE goals of the GCC countries (Saudi Arabia, United Arab Emirates, Qatar, Kuwait, Bahrain, and Oman) was provided, focusing on the primary projects and strategies designed to kick off this shift. An evaluation of the regional RE potential, an analysis of the current installed RE capacity and project pipeline, and a review of institutional and commercial frameworks were all part of this study's in-depth investigation of the GCC countries' renewable energy (RE) situation. Key financial, economic, political, legislative, technological, and environmental factors impeding RE implementation in the region were identified and explored. G. Muhammed discussed these countries and America's respective RE efforts [160]. Linear regression analysis determined how policies affect RE in the three selected countries. The findings showed that while policy assistance and regulatory instruments have the most effect, economic mechanisms are the most effective at increasing installed RE capacity. The US explored renewable energy sources for the benefit of Pakistan's economy and provided new job possibilities. Ahmad et al., in [161], aimed to identify methods for ensuring sustainable energy production and financial benefits. The paper also suggested putting resources into renewable energy systems with the lowest operational and external costs. It indicated that the government of Pakistan should encourage technological advancement in the nation's biomass resources because of their high potential benefits from a policy perspective. In addition, another developing country, an ASEAN member, is interested in several energy sources, including solar, wind, hydro, and biomass. S. Mekhilef et al. work in [162] underscores the significance of investigating renewable energy solutions to the rising expense of fossil fuels and greenhouse gas emissions. Legislation encouraging the use of renewable energy sources in both household and business settings has been passed by the Malaysian government, and a report that offers a concise summary of renewable energy in Malaysia, including information on current projects, projections for the future, and alternative energy policies were presented in [162]. To promote "smart, sustainable, and inclusive" growth in the region, the Europe2020 Strategy was presented in 2010 by I. Siksnelyte-Butkiene et al. [163], using the state-of-the-art multi-criterion decision-making (MCDM) technique to assess countries' progress towards the strategy's climate change and energy goals. The advancement of various countries was evaluated and compared using kernel-based comprehensive assessment (KerCA). Insights gained from analyzing how well the strategy was implemented can help shape and manage the dynamics of climate change and energy policy issues in the region, even during crises such as the COVID-19 pandemic or the Ukraine invasion. The innovative approach taken in the research was that the work assessed how effectively the objective was reached and how much was achieved beyond the initial objective.

Global consumption of coal, oil, and gas has reached unprecedented levels, reflecting the high demand for these fossil fuels. In response to the pressing need for sustainable energy sources, countries such as the United States, the European Union, and others actively promote and support the transition towards alternative energy solutions [66]. There is a noticeable upward trend in climate ambition and action within the public and corporate sectors.

The global energy boom since 2020, coupled with the impact of the COVID-19 epidemic, has led to an unprecedented surge in coal and fossil fuel demand [67]. However, with the estimation of Figure 2.12, which shows predicted sectoral demand, a reduction in the coming years is expected as there has been a noticeable global economic recovery, with a growing refocused investment plan in clean energy projects. Post-pandemic combustible fossil fuel consumption is predicted to peak in 2023, with road transport in 2025 and total transport in 2026. This pressing need has sparked an unparalleled surge in investments directed toward advancing clean energy technology, and the imperative to achieve climate targets necessitates a substantial surge in renewable generation by 2050 [57].

Sustainable development is closely linked to using renewable energy sources [45], as the economy relies on natural resources to provide consumer goods and services. The availability constraints and disadvantages of excessive use of these natural resources pose restraints to sustainable development. The UN's SDGs for 2030 established the need to address these challenges by setting targets for sustainable development, and in doing so, the critical link between renewable energy use and sustainable development became apparent. Among the 17 SDGs established by the United Nations is climate change action (i.e., Goal 13) through the promotion of environmental sustainability practices.

It has become necessary to stop or reverse the depletion of environmental resources by implementing national policies and plans prioritizing sustainable development. Goal 7 of the 2030 Sustainable Development Agenda established by the United Nations consists of the following [88]: universal access to affordable, secure, and modern energy services by 2030; strengthening international cooperation to facilitate access to renewable energy; increasing energy efficiency; and promoting investments in energy infrastructure and clean energy.

Achieving such a feat could significantly increase the share of renewable energy in the global energy mix by 2030 and double the global development rate to enable the population to afford the initial cost of the transition. The focus on renewable energy in SDG 7 is a prime example of this principle that synergizes the relationship between renewable energy and sustainable development.

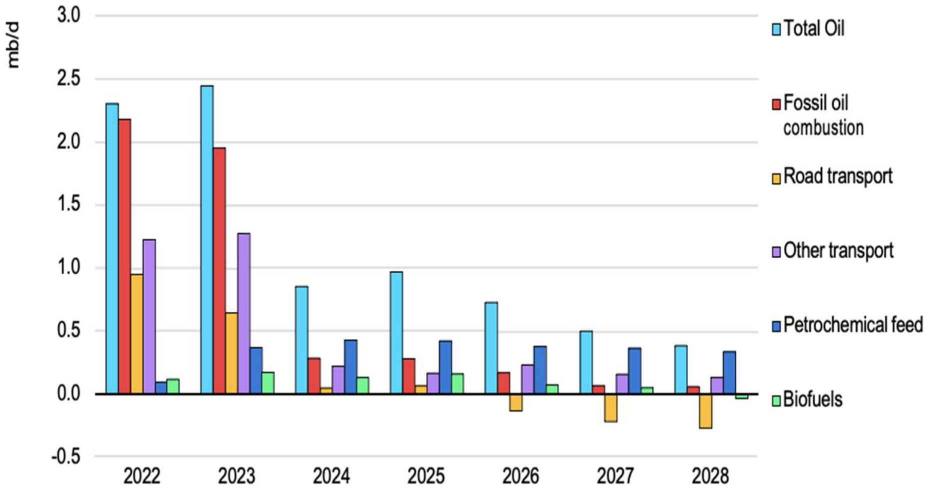


**Figure 2.12.** Forecasted growth in oil demand (per annum, between 2022 and 2028), according to the IEA Oil Report in [2].

The global movement towards low-cost, environmentally friendly energy systems is gaining momentum, necessitating a better understanding of the interconnectedness of energy and sustainable development [116]. Climate change and energy variability severely affect human society, the environment, and development. Renewable energy investment is widely accepted as a strategy to reduce global warming impacts and ensure long-term economic growth sustainability. Sustainable energy development involves expanding energy supplies and regulating demand to meet societal energy needs while minimizing greenhouse gas emissions and climate change impacts [164]. The difficulties posed by climate change have been exacerbated by global anthropogenic activities that release harmful greenhouse gases (GHGs) into the atmosphere [145]. The use of fossil fuels as an energy source has come under increased scrutiny because of efforts to reduce climate uncertainty. All parts of the world are feeling the effects of climate change, and the energy industry has received much attention because it is responsible for a disproportionately large percentage of these emissions. Since energy consumption is so important to economic growth, experts have continuously stressed the importance of large utilization of renewable energy sources across the globe [165], [166], [167], [168], [169], [170], [171], [172]. Currently, this has led several advanced countries to invest in several renewable energy projects while most developing countries are still striving to achieve 100% energy access and other development issues. Therefore, a growingly disproportionate share of global greenhouse gas emissions could be expected from developing countries should they follow the traditional path of industrialization towards achieving complete energy access [173].

Reviewing the literature using bibliometric analysis, X. Pan et al. [98] found that studies on the relationship between energy and sustainable development have increased rapidly in recent years. Low carbon emissions and efficient and sustainable energy systems provide great potential for advancing human flourishing, material prosperity, ecological equilibrium, and cooperative endeavours. To combat climate change, X. He et al. in [174] investigated whether countries with large investments in renewable energy should increase their spending on R&D. The findings demonstrate that investments in renewable energy generation can lessen the risks associated with climate change and cut down on export surpluses. Sustainable urbanization policies, improved use of natural resources, and more investment in renewable energy technology are all essential steps toward achieving SDG 13. Global leaders prioritize slowing climate change, urging both developed and developing countries to adopt low-carbon sustainable technologies that are both scalable and transferable. Numerous studies have investigated the potential synergies that could be realized on a national level and the trade-offs that must be made between the various aspects of sustainable development. Case studies on a national scale of Brazil, China, India, and South Africa are highlighted as examples from these studies, as summarized by K. Halsnæs et al. in [175]

Sustainable development has been advocated as a guiding principle to coordinate better efforts to tackle poverty and climate change. These countries may be able to accelerate their development efforts and reduce their carbon footprints at the same time if climate change is factored into their sustainable development strategies, developing adaptability in the face of climate change and the possibility of alternative national development plans for infrastructure [175]. China’s energy demand, supply, and emissions, focusing on global, regional, and local environmental and health concerns, were analyzed by X. Ren et al. in

[176] while addressing equity issues in climate change and the connection between redefining development goals and sustainable development. It discusses non-fossil fuels, natural gas switching, economic reorganization, and clean coal technologies for reducing emissions and energy security. It emphasizes improving energy efficiency and integrating renewable energy into rural development [176]. The study by S. S. Mutanga et al. in [177] showed that African countries need infrastructure for sustainable development goals such as human growth, poverty eradication, and climate change mitigation, and further stated that the G20 Agenda for Africa in [178] should align with African initiatives, the SDGs, and the Paris Agreement; promote low-carbon development; eliminate subsidies; establish a carbon price; and create a level playing field for low-carbon technologies. M. Tosam et al.'s work in [179] examined Africa's disposition to climate change and its potential for long-term development. Africa is the most susceptible region globally, facing starvation, illness, and financial loss due to environmental degradation and extreme weather events. The continent's fragile political and economic systems are threatened by climate change. It argued that investments in renewable energy, good governance, and traditional values, such as environmental preservation and women's economic empowerment, are essential for effective climate change mitigation and sustainable development [179]. With a focus on regional and local initiatives, D. Streimikiene et al.'s work in [179] analyzed Lithuania's national energy and climate change policy. It offered a framework for regional solutions to climate change mitigation in the context of national and transnational energy, climate change, and rural development policies.

For long-term progress in green energy economy for sustainable growth (EESG) domains [180], a country must shift to a green economy. Renewable energy is indispensable for sustainable development and the fight against global warming [181]. Enhanced energy resource potential forecasting, more reliable renewable energy resources, and energy efficiency incentives could support countries' policies for renewables in support of climate change actions [182]. Energy efficiency, renewable energy, mobility, and sustainable land use are only some examples of climate change policies that can help advance the sustainable development agenda [150], [183], [184], [185], [186], considering the distributive consequences of not making responsive and immediate plans to tackle climate change issues and the consequences on both social and economic development, vulnerability to climate change effects, and adaptive capability, future agreements on mitigation, public trust, and adaptation are needed.

To effectively combat climate change, it is crucial to comprehend the complexity, unpredictability, and hazards related to future climate change [187]. Following pertinent national green development strategies and policies, utilizing science, technology, finance, and city governance to actively address urban climate change issues, such as improved adaptation and mitigation measures, and carefully selecting development pathways can significantly improve climate resilience [187]. Income, poverty, water stress, food access, sustainable energy use, energy security, and ocean acidification are the only indicators of sustainable development and climate change that can be analyzed. K. Akimoto et al. [188] stressed the importance of a well-thought-out strategy for economic growth to deal with climate change and sustainable development indicators. Integrative assessment frameworks are often applied to analyze these metrics objectively [189], [190], [191], [192], [193], [194]. Synergizing energy development with long-term sustainability is an area that necessitates more study and further investigation as the current global paradigm views energy as a subset of climate change policy's many related components. Therefore, national energy policy instruments and frameworks are crucial for mitigating global climate change by addressing fossil fuel geopolitics, renewable energy technology development, and national power system planning. Addressing core societal concerns such as energy security is essential for achieving climate goals and sustainable development.

## 2.10 Conclusion

Given that the average energy generation life cycle is about 25–30 years, the world is just about one-quarter of an investment cycle away from 2030. This chapter emphasizes the urgency of addressing current and emerging energy issues within the updated themes of SED presented in this work and, more particularly, the importance of clean energy financing and renewable energy dominance. Any investments made in current energy generation must be able to work in concert to meet society's needs in the present while limiting any further carbon emissions to keep the environment protected for future generations. Hence, continuous investments in fossil fuels could lead to stranded assets and underutilization within the regular life cycle of electricity generation plant operations. Therefore, significant investment in clean and sustainable energy systems could ensure the operational longevity of generation facilities beyond the year 2030. With this in place, the global energy system can be sustainable, helping nations focus on the other key development needs of society that make up the other goals of the United Nations' SDG, such as discussed in section 2.4.1, while reducing the impact of climate change through energy development.

The world's total energy development has continuously seen an increased growth rate of renewable sources' contribution to the total global energy mix during the past decade. However, the penetration of RE comes at a high initial cost that requires a large and unprecedented financial investment from government, private, and corporate entities. Consequently, countries and governments are required to assist this movement by developing policies that support the nationally determined contribution (NDC) initiative for each country to comply with the COP21 Paris Agreement's objectives for reducing greenhouse gas emissions and adapting to climate change. It is unfortunate that even though there are commitments by many of the countries making up the 195 members of the UNFCCC, as can be found in the NDC registry in [91]. Hence, there is a need for stricter policy measures, better Carbon budgeting and energy financing to reduce global emissions, as the current NDCs are not sufficient.

A recordable investment into fossil fuels continues, as can be seen in our analysis, where finance allocated by the G20 countries for clean energy constitutes only 38% of the total, which is somewhat smaller than the allocation for fossil fuels at 43%. The remaining 19% is designated for various other forms of energy that are either clean or fossil fuels, posing a continual challenge to ambitions addressing climate change.

Therefore, clean energy financing policies and support should be increased by developing an evaluation system and information disclosure criteria compatible with developmental issues and energy innovation to reduce emission levels in the drive for sustainable development. Such evaluation systems should employ an integrative approach in assessing and determining the right energy financing mechanisms for transition into globally sustainable energy systems and sustainable development. A typical example may be redefining NDC through a centralized emission budgeting strategy for global or regional stock-taking aimed at identifying the best options for emissions reduction investments. For instance, the NDC from the EU addresses greenhouse gas mitigation from a regional perspective. In this way, less adverse compromise on individual countries' developmental issues could be achieved through the right sharing ratio for both clean energy funding and emission reduction expectations. A possible outcome from such a regional evaluation system could help provide clarity on the exact percentage of renewables in both the national or overall global energy mix and the right energy finance investment options that put every country in an advantageous position to meet the goal of low-carbon economic transformation and to stay within the 1.5 – 2.0 °C scenario of the Paris Agreement.

# Chapter 3

## Towards the 1.5$^o$C climate scenario – the Environment Model

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*Book Chapter on Global Warming – A Component of Climate Change: IntechOpen* [195].

### 3.1 Introduction

The Paris Agreement's requirements for lowering greenhouse gas emissions and adapting to climate change require countries to be mandated to facilitate this movement by building policies to support the National Determined Contribution (NDC) initiative for each country. The Paris Agreement requires all nations to contribute "nationally determined contributions" (NDCs) to the global effort to mitigate climate change. Countries publicly disclose their post-2020 climate change actions of reducing greenhouse gas emissions, establishing a balance between richer countries and developing nations, and promoting equality, sustainable development, and poverty eradication [77]. These goals are vital development priorities for many emerging nations. A simplified earth system model was used in [151] to evaluate the global temperature slowdown in the NDC scenario (T = 0.6°C) and identify the causes in certain locations. The Organization for Economic Co-operation and Development (OECD) and Asian Nations (R5ASIA) were the top two contributors, with 39.3 and 36.8 per cent, respectively. The next two largest contributors were the Latin American and Caribbean (R5LAM) and Middle Eastern and African (R5MAF) areas, with 11.5% and 8.9%, respectively. The Reforming 5 Economies Forum (R5REF) is the remaining 3.5%. The extent to which a region pitches in to help cut carbon emissions is a major factor. Short-lived aerosols' influence on lowering $SO_2$ levels in R5ASIA was modest but significant [151].

In the study by Koven C. et al. [196], $CO_2$ concentrations fall below pre-industrial values when cumulative $CO_2$ emissions approach zero through negative $CO_2$ emissions, yet long-term climate change persists, guided by multi-century dynamical processes. Even if commitment to maintaining a consistent atmospheric composition and a steady stream of emissions, the global mean temperature and sea level would continue to increase [197]. A study by Grigoroudis E. et al. [198] explored the best emissions policies using the emission plans of only China and the USA that are compatible with temperature limitations. The findings indicate that negative emissions and severe cuts can maintain temperature stability of 2.5ºC. However, relying on future technical advancements to make negative emissions feasible might lead to ongoing carbon releases and irreversible climatic implications. Jung T. et al. [199] examined the financial cost, risk, and feasibility of lowering greenhouse gas emissions using a general equilibrium model and many burden-sharing schemes. Evaluations include one extended NDC scenario and three 2050 scenarios. The modelling results suggest that a GHG reduction in the Korean economy might cost between USD 100 and USD 350 in 2050, compared to the NDC extended scenario. Without a major economic and energy infrastructure overhaul, reducing greenhouse gas emissions in Korea would be costly.

Using a shared socio-economic pathway (SSP) of 1 - 2.6 ºC, the study by Vakilifard. et al. in [200] evaluated the advantages of introducing negative emission technologies in the global warming response to cumulative carbon emissions beyond 2050. The effective zero emissions commitment and the global warming response were evaluated over 86 unique model realisations. After net-zero emissions are achieved, the capacity to fulfil climate objectives and avoid further warming is improved by including negative emissions.

The findings from these studies highlighted above, and many others, such as the ones in [56], [74], [201], [202], [203], have shown that reducing emissions should not be a delayed option in energy and climate policies or the effort to only selected countries. For instance, the effect of the USA's withdrawal attempt from the Paris Agreement in 2017 was evaluated to increase strain on the global average of emissions reduction as well because of high costs on other countries [201]. The urgent need to combat climate change has led to the development and implementation of various policies and commitments worldwide. Among these, the National Determined Contributions (NDCs) under the Paris Agreement stand as a crucial framework where countries pledge their efforts to reduce greenhouse gas emissions [91].

## 3.2 Structure of the Chapter

This chapter is divided into eight sections. The first section introduces the National Determined Contributions (NDCs) and the urgent need to revisit the commitments. In the second section, the chapter structure is outlined with the contribution in the third section. The rationale for the environmental model is primarily to simulate the impact of different NDC commitments as policy scenarios and climate scenario outcomes. The fourth section gives a brief on historical emissions versus average global temperatures, global renewable energy progress by the major $CO_2$ emitters and the global average, and the updated NDC of these countries or regions. Section five defines and describes the methodology for the simulation, while section six defines the datasets, inputs, and scenario definition of the hypothesis. Section seven presents the results and discussion and the proposed way forward. Section eight concludes the chapter, laying out a foundation for Chapter four.

### 3.3 Contribution and Structure of the Chapter

This chapter uses a system dynamic approach embedded in an IAM tool to examine the updated NDCs and classify all the countries under China, the USA, India, the EU, the Rest of Advanced Countries, and Rest of the Developing countries to study the effect of the current NDC on global temperature levels, and what best reduction would result in the 1.5°C scenario. Pathways that could facilitate the 1.5°C scenario are proposed.

### 3.4 Rationale of the Environmental Model

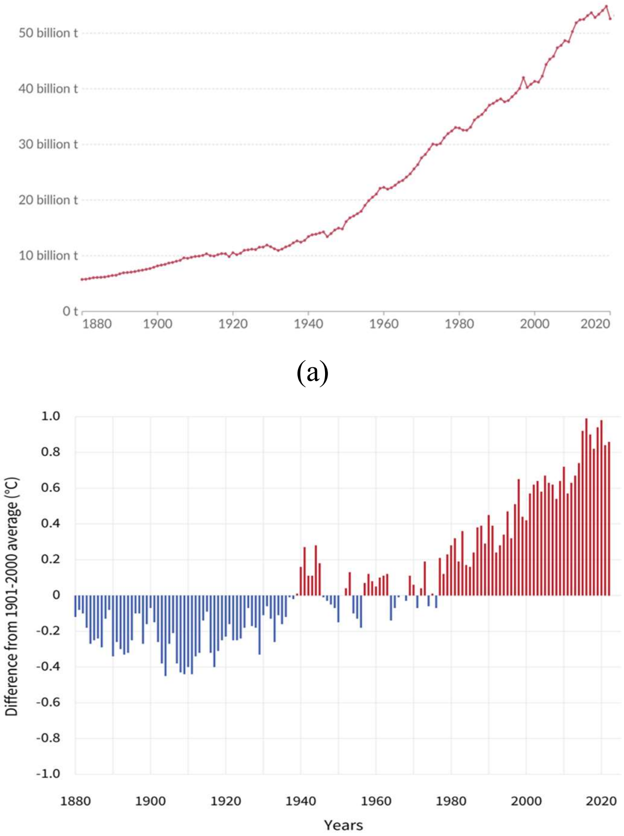
The ongoing discourse on climate legislation underscores the importance of enhancing and executing NDCs to achieve the objectives outlined in the Paris Agreement. It emphasizes the need for meticulously tailored policies and strategies for individual sectors to successfully attain the ambitious objectives of carbon mitigation, as delineated in global accords, particularly the Paris Agreement. Examining the effectiveness of Nationally Determined Contributions (NDCs) in reducing global temperatures to below 2°C as stipulated by the Paris Agreement goals is imperative. Using fractional integration and cointegration methods, the research by Gil-Alana [204] examines the connection between $CO_2$ emissions and global temperatures. The results for the short-term panel dataset contradict the hypothesis of cointegration since the orders of integration are different for the two variables. However, long-term time series data indicates a lasting positive correlation between emissions and temperatures [204]. It is also important to note that the emissions accumulation in the atmosphere lasts for a long period, enabling the noticeable effects on global temperatures.

A dynamic simulation framework is useful in predicting variations in global temperatures under various policy scenarios of emissions reduction, which is the aim of this study with the use of a just and fair transition approach. The just transition concept is a philosophical paradigm that promotes social and economic justice in the transition to a low-carbon economy [205], [206], [207]. It prioritizes equity, inclusivity, job creation, environmental justice, worker support, and sustainable development by employing strategies for reducing emissions. These strategies include investing in green jobs, transitioning to renewable energy, carbon pricing, regulatory policies, infrastructure investment, community engagement, education, and training. These strategies aim to create sustainable employment opportunities, reduce pollution, and protect vulnerable communities. By embracing these principles, policymakers, businesses, and communities can work together to transition to a low-carbon economy that promotes environmental sustainability and social justice, making the journey towards a more sustainable future fair and inclusive.

## 3.5 Progresses in Global Emissions, Average Temperature Rise, Renewable Energies, and Commitment to Emissions Reduction

### *3.5.1 Historical Emissions versus Average Temperature Rise Level*

The continuous increase in the emissions level is shown in Figure 3.1 (a), with experience in increasing average temperature as well, beyond the pre-industrial level, as indicated in Figure 3.1 (b). Consequently, there has been resulting global warming and adverse effects that distort the natural ecosystem.



(a)

(b)

**Figure 3.1.** Historical emissions versus average temperature rise level. (a). emissions growth, according to Ritchie H. et al. [208] and Jones M. et al. [209]. (b). global average changes in surface temperature 1880 – 2022, according to NOAA report [2].

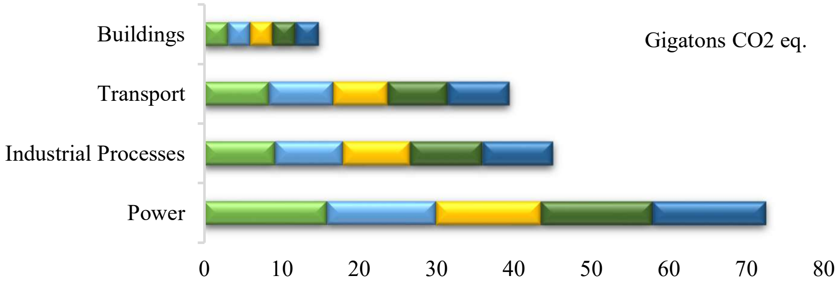
Greenhouse gas emissions (GHG) can be categorically divided mainly into emissions from $CO_2$ and other gases such as $CH_4$, $NO_x$, hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF6), and Perfluorocarbons (PFCs) based on the Kyoto Protocol [80]. The first constitutes most of the emissions from energy production and consumption, often found in the power, industrial processes, transport, and building sectors. Understanding the effects of the emissions in terms of global warming potential (GWP) is often made with reference to its equivalence with $CO_2$. For instance, 1, 25, 298 are regarded as the equivalency factor for $CO_2$, $CH_4$, and $N_2O$ in terms of 100 - year GWP. Similarly, HFCs (675 and 14,800 for $CH_2F_2$ and $CHF_3$), PFCs: 7390, 12,200, 8,830, 8,860, 10,300, 13,300, 9,300 for $CF_4$, $C_2F_6$, $C_3F_8$, $C_4F_{10}$, c-$C_4F_8$, $C_5F_{12}$, and $C_6F_{14}$, respectively, $SF_6$: 22,800.

All the gases have significant impacts on global weather patterns, which last for years; hence, they are determined by adding the radiative forcing caused by a gas's pulse emission over a certain amount of time. However, an evaluation of the final implications of climate change is not directly tied to these calculations. As a result, Kirschbaum M. [53] developed a new metric called the climate-change impact potential (CCIP), which evaluates the significance of pulse emissions of different gases, such as $CO_2$, methane, and nitrous oxide. Three categories of consequences are identified: warming rate, cumulative warming, and temperature rise. According to the CCIP, long-lived nitrous oxide has a greater impact than short-lived methane over 100 years.

In the next section of this study, the emissions from the two categories of GHG are presented within the last five years.

### *3.5.2 Short-Term Level Emissions Trajectory*

Figure 3.2 shows the emissions trends from energy (i.e., $CO_2$ emissions) during the last five years, while Figure 3.3 compares emissions of Figure 3.2 with those obtained from other gases.



| | Power | Industrial Processes | Transport | Buildings |
|---|---|---|---|---|
| 🟩 2018 | 15.88 | 9.19 | 8.42 | 3.11 |
| 🟦 2019 | 14.07 | 8.76 | 8.26 | 2.91 |
| 🟨 2020 | 13.57 | 8.71 | 7.09 | 2.85 |
| 🟩 2021 | 14.39 | 9.31 | 7.73 | 3.01 |
| 🟦 2022 | 14.65 | 9.15 | 7.98 | 2.97 |

**Figure. 3.2** Global $CO_2$ emissions by Sector 2018 – 2022. Data from the IEA report and Ritchie, H. et al. in [23][210], respectively.

Over half of all emissions (i.e., 60.5, 55.6, 54.1, 55.64, and 56% between the years 2018 to 2022, respectively) come from the energy processes, where the burning of fossil fuels is the norm in the power sector with the highest value of $CO_2$ emissions contributions for all the years presented in Figure 3.4. Followed by industrial operations like cement manufacturing and chemical manufacturing also contribute significantly to methane emissions, as do agriculture and land use. Emissions from the combustion of fossil fuels are a huge problem, and transportation modes, including cars, planes, ships, and trains, all contribute to this problem. Buildings contribute to emissions from heating, cooling, and electrical use because of the energy used for these purposes.

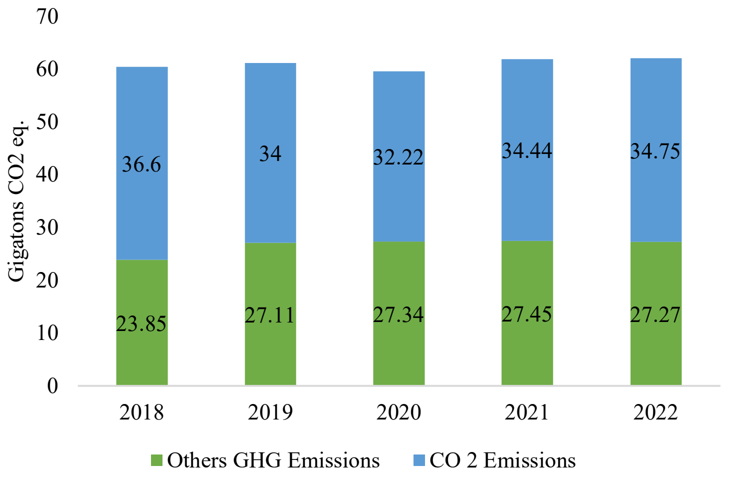


**Figure. 3.3.** Global GHG emissions from 2018 – 2022. Data from the IEA report and Ritchie, H. et al. in [23][210], respectively.

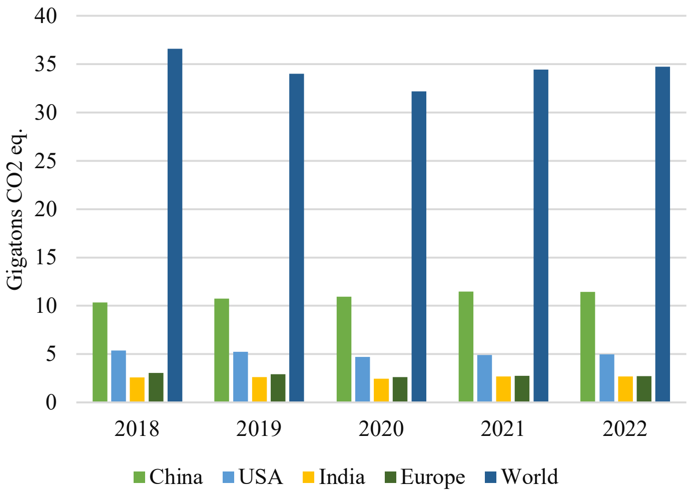


**Figure. 3.4.** Top $CO_2$ emitting countries with emission values from 2018 – 2022. Data from the IEA report and Ritchie, H. et al. in [23][210], respectively.

### *3.5.3 Global Renewable Levels Progress*

The use of these renewable energy technologies not only helps the economy, society, and the environment but also advances the cause of sustainable development. Renewables account for less than two-thirds of total energy consumption and 85% of total power output [211]. The amount of renewable energy that must be deployed must be increased at least six times over what is now planned to keep global warming to far below 2°C; hence, decarbonisation strategies such as the ones highlighted by Akpan J. et al. in [212], for carbon emission control is critical. If the global energy system is transformed, everyone should have access to less expensive and reliable energy at a higher level of security. Theory, ideologies, innovations, global needs, and policy conceptions, as well as implementation, continue to influence the adoption of renewable energy technology in a wide range of applications and sectors. Countries striving to achieve a high level of reliance on renewable energy sources employ a diverse range of renewable energy technologies. Factors like geographical location, resource availability, technological capacity, governmental aims, policy frameworks, infrastructure development, and economic situations influence the variability of renewable energy sources. About 30 countries that have achieved nearly 100% renewable energy (RE) utilization exhibit a predominant reliance on a specific RE source, such as wind, solar, or geothermal [72]. Notably, the most prevalent RE source among these countries is hydropower, accounting for a minimum of 70% of its RE generation. China, the United States, India, and the European Union, which are the largest emitters of $CO_2$, are yet to reach even a 40% RE in their national electricity mix, as shown in Figure 3.5. However, these countries exhibit a diverse range of renewable energy sources within their overall energy portfolio, including hydropower, wind power, and solar energy. The United States and India contain a diverse range of renewable energy sources in their respective portfolios, including wind, solar, hydropower, and biomass. There is a variance in the proportion of renewable energy sources among member states of the European Union, with significant progress recorded in Germany and Denmark as they transition towards renewable energy. Unfortunately, geothermal energy has received relatively limited attention in many nations, potentially attributable to the significant upfront costs associated with infrastructure development and execution.

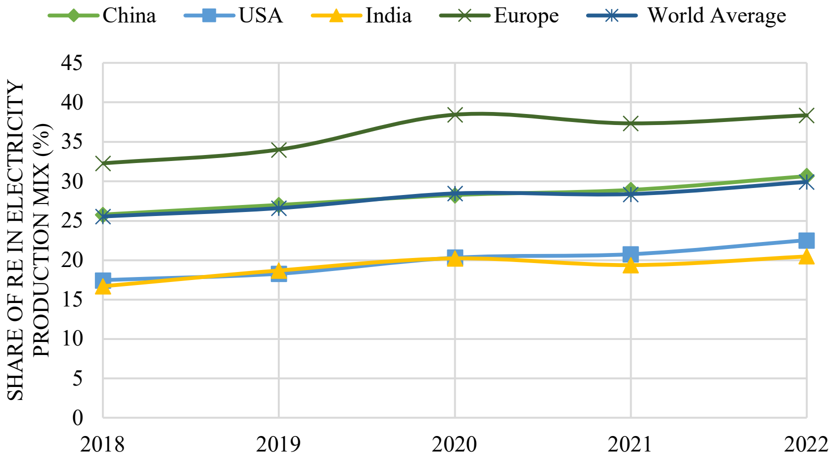


**Figure 3.5**. Share of RE in electricity production 2018 – 2022. Data from Ritchie, H. et al. [213]

To keep this value well within the 1.5 - 2°C range and mitigate the consequences of climate change, such as drought, flood, and heat wave, existing and projected policies have been made by several countries. Meanwhile, the current finance set aside to facilitate clean energy projects to curb the emissions from the different contributing sectors and countries is not sufficient to achieve the Paris Agreement of COP21 [57], [66].

### 3.5.4 *Updated National Determined Contribution of Top $CO_2$-Emitting Countries*

The use of these renewable energy technologies not only helps the economy, society, and the environment but also advances the cause of sustainable development [5]. And because of the urgent need to keep the global temperature within the $1.5^0$C scenario, many countries, herein top emitting countries, have proposed and are working towards this goal by introducing national energy policies that could drive this change. Mostly the transition to the use of renewable energies. These policies are summarized in Table 3.1 below.

**Table 3.1.** Updated policies of selected top GHG emitters by energy in response to the 1.5$^0$c scenario issues (between 2020 to 2023)

| Category | Country/Region | NDC Highlights | Country/ Region | NDC (Emissions Reduction) | To Address 1.5$^0$C Scenario Issues | Ref |
|---|---|---|---|---|---|---|
| A | China | Table 2.5 in Chapter 2 | China | 65% | Partial | [57][102], [117] |
| A | USA | Table 2.5 in Chapter 2 | USA | 50-52% | Partial | [57][103] |
| D | India | Table 2.5 in Chapter 2 | India | 45% | Partial | [57][104] |
| A | Europe | Table 2.5 in Chapter 2 | Europe | 40% | Partial | [57][105] |

A-Advanced, D-Developing

## 3.6 Methodology

### *3.6.1 Overview*

The process of simulating pathways towards limiting global warming to 1.5°C requires the use of complex climate models and scenario studies. These models are designed to incorporate various factors influencing the climate system, such as greenhouse gas emissions, land use changes, and aerosols. They help predict potential climatic impacts over time resulting from various emission reduction strategies and policies. The Intergovernmental Panel on Climate Change (IPCC) frequently assesses diverse emission scenarios and their corresponding implications for global temperature increases. Climate models are sophisticated tools used to simulate the potential effects of various emission scenarios on the Earth's climate system, considering complex interactions among the atmosphere, oceans, land, and ice. Mitigation methods have been complied with by the IPCC report, which includes renewable energy sources, energy efficiency enhancements, reforestation efforts, carbon capture and storage initiatives, and modifications in agricultural practices. Simulations also consider potential adaptation actions required to address climate change consequences, such as uncertainties related to human behaviour, technological improvements, natural variability, and policy changes within the climate system. Policy assessments evaluate the viability and efficacy of various policies and measures designed to mitigate global warming impacts.

### *3.6.2 Existing and Related Climate Models and Model Selection for Study*

Long-term data (temperature and GHG concentrations) spanning thousands of years is required for studying climate change. The study of current climate change and the development of projections for the future requires a solid foundation from existing climate change models. Based on historical findings and trends, many tools have been used to reconstruct the temperature record and predict GHG values and vice versa. The key tools, models, and their corresponding findings are presented in Table 3.2 below.

**Table 3.2.** Key emerging integrated climate assessment models

| **Year of Development** | **Climate Model (s)** | **Organization/Country** | **Baseline Emissions CO$_2$ eq. (GTons)** | **Baseline Temperature Rise Level ($^{o}$C)** | **Other Scenarios** | **Period** | **Ref** |
|---|---|---|---|---|---|---|---|
| 2023 (Most updated version) | C-ROAD | MIT/Ventana System/Climate Interactive | 66.8 | 3.32 | U/D | 2023 - 2100 | [27] |
| 2021 | Model for the Assessment of Greenhouse Gas-Induced Climate Change (MAGICC) | Climate Resource | 126.29 | < 4.0 | 1.5$^{o}$C<br>2.0$^{0}$C | 2020 - 2100 | [214] |
| 2023 | Global Energy-Climate (GEC) | IEA | - | A | NZE Scenario<br>AP Scenario<br>STEP Scenario | 2023 - 2100 | [145], [215] |

U/D – User dependent, NZE – Net Zero, Announced Pledges (AP), STEP (Stated and Planned), A – Assumed based on temperature projections from IPCC reports.

The three models and tools (C-ROAD, MAGIC, GEC) highlighted in Table 3.2 are all integrated assessment tools which extract insights and data from several existing and conventional climate models, meteorological, macroeconomic, and sector-by-sector data. The GEC model is used mainly to study possible future states of transition into net-zero Carbon emissions from energy systems only while keeping in view several sets of assumptions consistent with the Sixth Assessment Report by the IPCC to limit global warming to less than 1.5 °C (with a minimum of 50% probability) with a negligible possibility of exceeding that objective [215]. In the temperature projection part, IPCC scenarios are used. The IPCC scenarios are majorly derived from the MAGICC model [214]. The MAGICC is a less complicated climate system model which anticipates future climate change and Earth's component interactions with uncertainty and compares its outcome based on the feedback from over 400 climate simulation models embedded in it. MAGICC simulates the carbon cycle, methane cycle, and anthropogenic aerosol emissions in four boxes representing the Earth's land and ocean. Hence, climate change, greenhouse gas concentrations, effective radiative forcing, temperature change, Earth system heat absorption, and sea-level rise are projected [214]. The drawback with the MAGICC is its set temperature projection limitation, making it difficult to assess the exact estimate values of other constituting factors that influence temperature changes. Also, the MAGICC does not allow for user definitions to ascertain possible feedback based on inputs. Therefore, C-ROAD, with several additional capabilities highlighted in Table 3.3, has become more pertinent and open-source for user interaction and feedback for policy simulation and decisions.

As already mentioned in sections 3.1 - 3.2 of this chapter, the objective of the chapter is to simulate different policy measures available and may be required to transit towards the 1.5°C scenario. The goal of this simulation procedure is to ascertain the different NDC composition pathways under the context of climate justice needed by all countries and or regions to reduce emissions. The simulation is done to ascertain the possible reduction value at critical years up to the year 2100. A schematic of how the model's process flows is represented in Figure 3.6, as embedded in the tool used, which is described in the next section.

### *3.6.3 Description of Tool Used for the Study and Governing Equations*

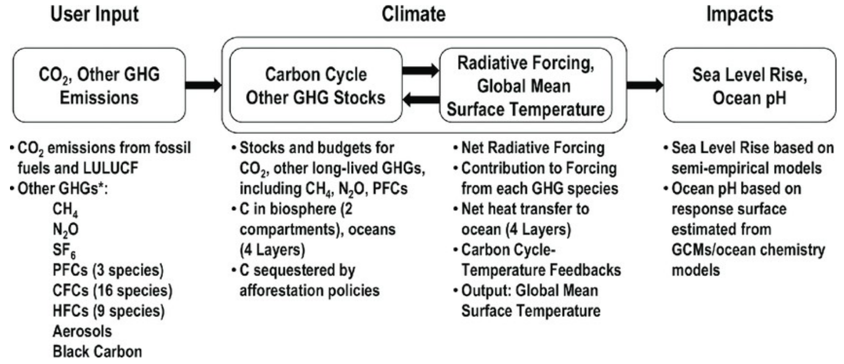
The tool used in this study integrates climate science, economics, and policy analysis to develop a comprehensive and reliable simulation framework. Using fundamental principles, C-ROADS is a real-time system dynamics model that allows users to input actions to reduce GHG emissions from land use and forestry. For studying complex systems across time, Jay Forrester developed system dynamics in the 1950s [29]. The system dynamics employs system thinking to analyze the dynamic interplay and feedback between various system components and factors [34], [216]. A system dynamics model's structure and behaviour may be shown using stock and flow as in Figure 3.6 for this chapter. Users can see the system's responses through simulations utilizing system dynamics models. They also investigate the impact of dynamic complexity on system behaviour and unintended outcomes and can use it to develop a case for business [35], technology – market – Carbon dynamics emission [217], strategic scenario forecasting [218], and as a guide for other policy decisions.

The C-ROADS integrates national and regional emission and land use sectors, aiming to understand how national and regional commitments could contribute to climate objectives. It generates findings efficiently and is used to support other integrated assessment models, calibrating results using larger disaggregated models [30]. The capabilities and limitations of the C-ROADS based on the model technical reference in [30] are presented in Table 3.3 below.

**Table 3.3.** C-ROAD model capabilities and limitations

| Capability | Description |
|---|---|
| Accessibility | The model provides real-time features through a user-friendly graphical interface. |
| Consistency | The findings of the Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5), along with other organizations and knowledge derived from comprehensive models, align consistently with the outcomes of the simulator. |
| Flexibility | The model can accommodate a diverse range of user-defined scenarios, which can vary in terms of their complexity. |
| Robustness | The model effectively encompasses the inherent uncertainty around the potential climatic effects that are linked to decisions regarding emissions. |
| Transparency | There is access to the equations; they may be checked, and they are displayed graphically. |
| Understanding | The causes of the model pattern’s expression can be identified and traced to real behaviours. |
| Limitation | No economic assessment considerations, less spatial resolution, and less detailed assessment of climate impacts |

Figure 3.6 depicts the C-ROAD architecture for the emissions versus global temperature transition.



Key Stocks (Carbon Cycle and other GHG) and Key Flows ($CO_2$ and other GHG Emissions)

**Figure 3.6.** C-ROADS model architecture [30]. **Note:** Key stocks (carbon cycle and other GHG stocks), key flows (CO2 and other GHG emissions), and feedback (temperature feedback based on carbon cycle from ocean-atmosphere interaction owing to radiative forcing, cooling feedback and heat contents).

The C-ROADS has three phases, as shown in Figure 3.6. The user input, climate model, and the impact phase. The user input phase allows users to set the year of peak emissions, start reduction, and level of effort to prevent deforestation and promote afforestation. The reduction levels are a function of the summation of the aggregate percentages of greenhouse gas emissions. In the second phase, the climate model is a fifth-order linear system with three negative feedback loops that control deep ocean warming ($\boldsymbol{H_d}$, and $\boldsymbol{R_d}$) as well as warming in the atmosphere and surface ocean ($\boldsymbol{H_s}$, and $\boldsymbol{R_s}$), respectively. Radiative forcing $\boldsymbol{F_r}$, cooling feedback ($\boldsymbol{F_o}$, and $\boldsymbol{F_d}$), and heat content ($\boldsymbol{H_d}$, and $\boldsymbol{H_s}$) all have an impact on the first-order ocean warming response. Based on the climate interactive technical reference in [30], the equation governing the variables can be represented in the relation of equation 1.1 – 1.6.

$$\boldsymbol{T_s = \frac{H_s}{R_s}} \tag{1.1}$$

$$\boldsymbol{T_d = \frac{H_d}{R_d}} \tag{1.2}$$

$$\boldsymbol{H_s = \int (F_r(t) - F_o(t) - F_d(t))\, dt + H_s(0)} \tag{1.3}$$

$$\boldsymbol{H_d = \int ( F_d(t))\, dt + H_d(0)} \tag{1.4}$$

Where ($\boldsymbol{T_s}$, and $\boldsymbol{T_d}$) are the surface and deep ocean temperatures, respectively. ($\boldsymbol{F_o}$, and $\boldsymbol{F_d}$) are the cooling feedback, outgoing radioactive flux, and heat flux to the ocean, respectively.

$$\boldsymbol{F_o(t) = \lambda * T_s} \tag{1.5}$$

$$\boldsymbol{F_d(t) = R_d * \frac{T_s - T_d}{\tau}} \tag{1.6}$$

Where $\boldsymbol{\lambda}$ and $\boldsymbol{\tau}$ are climate feedback parameters and heat transfer constant.

The radiative forcing $\boldsymbol{F_r}$ from $CO_2$ is a logarithmic function of atmospheric $CO_2$ concentration [49][219], while the total $\boldsymbol{F_r}$, required to quantify $CH_4$ and $N_2O$ forcings, is smaller than the sum of the $\boldsymbol{F_r}$ for either gas alone. F-gas forcings are the product of

$CO_2$ concentration and radiative forcing coefficient, while other forcings from aerosols and tropospheric ozone are exogenous time-varying parameters. $CO_2$ concentrations are a function of the ratio of atmospheric $CO_2$ concentrations to pre-industrial atmospheric $CO_2$ concentrations, as depicted in equation 1.7.

$$\mathbf{CO_2\ \mathit{concentration}} = \frac{\mathrm{CO}_2\ \mathit{atm}}{\mathrm{CO}_2\ \mathit{pre\text{-}industrial\ atm}} \tag{1.7}$$

In equation 1.8, the equilibrium temperature response $\boldsymbol{T_E}$ , it is determined by the radiative forcing coefficient and climate feedback parameter.

$$\boldsymbol{T_E} = \frac{\kappa}{\lambda} * \frac{In\,(\frac{\mathrm{CO}_2\ atm}{\mathrm{CO}_2\ pre\text{-}industrial\ atm})}{In\,(2)} \tag{1.8}$$

On running the model, the output shows the temperature changes with the emissions, which can be extracted for further analysis. The last phase, the impact phase, produces the consequence effect of temperature changes on sea level rise with flood risk map, pH level, ocean acidification, crop yield decrease, possible death from extreme heat, and animal and plant species loss.

## 3.7 Dataset and Definition of Scenarios

### *3.7.1 Dataset*

Under full yearly resolution up to 2010, 6 regions modes were assumed, categorized into China, US, India, EU, rest of advanced Countries, and the rest of developing countries. Both the techno-economic and socio-economic factors play a role in forecasting $CO_2$ emissions and temperature level changes. The main input variables for estimating emissions in Gigatons per $CO_2$ equivalent and global temperature changes are based on the features of equation (1.1) – (1.8).

The model input baseline values of countries and regional generation profiles used are extracted from recent data from the following sources, as stated in Table 3.4.

**Table 3.4.** Model input data and sources

| Input | Description | References |
|---|---|---|
| Historical Country-level data | 1. $CO_2$ emissions from fossil fuels<br>2. $CO_2$ emissions from land use | [27] |

| | | |
|---|---|---|
| | 3. GDP<br>4. Population growth prospects<br>5. Other GHGs | |
| Carbon cycle and climate sector data | The carbon cycle modelling approach uses historical country data for its estimation. Following equation (1.1) – (1.8) and other relevant approaches | [27], [30] |
| NDC | The Nationally Determined Contributions (NDC) are extracted from the UNFCCC registry, and with equation (1.9), the emissions reduction rate is determined per annum for the baseline and other scenarios. | [91] |

$$e_r = \left[\frac{NDC_i}{100}\right]^{1/n} \tag{1.9}$$

Where $e_r$ is the annual emissions reduction (expressed in percentage), NDC is the National Determined Contribution for each country *i,* and n is the number of periods (in years) to fulfil that commitment, starting from the year the NDC was submitted to the UNFCCC under the registry in [91]. The baseline emission reduction rate per annum, as calculated, is presented in Table 3.5.

**Table 3.5.** Annual emissions reduction based on updated policies of selected top GHG emitters by energy in response to the 1.5 $^0$C scenario issues (between 2021 to 2023)

| **Category** | **Country/Region** | **Annual reduction (%)** | **NDC (Emissions Reduction Targets)** | **NDC Target Year** |
|---|---|---|---|---|
| A | China | 0.94 | 65% | 2030 |
| A | USA | 0.928 | 50-52% | 2030 |
| D | India | 0.915 | 45% | 2030 |
| A | Europe | 0.903 | 40% | 2030 |
| D | Rest of Advanced Countries (RAC) | NU | - | P/D |
| A | Rest of Developing Countries (RDC) | NU | - | P/D |

*NU – Non-Uniform, P/D – Partly Defined and not same across all the developing and advanced countries.

### *3.7.2 Scenario Definitions*

The different simulation input data in the form of NDC based on each scenario is made as a hypothesis as in Table 3.6 and described in Appendix, Table A1.

**Table 3.6.** Scenario definitions and hypothesis

| Scenarios | Hypothesis | Ref. |
|---|---|---|
| Baseline Case | Without NDC | Based on historical country-level data available through [27] |
| Announced Policies Type 1 | With NDC only for China, Europe, USA, and India | Table A1 |
| Announced Policies Type 2 | With the same NDC of China, Europe, USA, India, the Rest of the Advanced Countries (RAC), and the Rest of Developing Countries (RDC) | Table A1 |
| 2.0 ºC Degree Celsius Scenario | Increased NDC but equal shares across all regions | Table A1 |
| 1.5 ºC Degree Celsius Scenario | Increased NDC but equal shares across all regions | Table A1 |

## 3.8 Results and Discussion

### *3.8.1 Findings*

The results of the simulation are presented in this section under two categories: policy versus global temperature rises in Figure 3.7 and policy versus emissions in Figure 3.8. The detailed emissions values per country or region (i.e., USA, EU, Other Developed Countries, China, India, and Developing Countries) are included in the Appendix, Figure A1 – A5 for all the global temperature rises.

The simulation results of the emissions reduction scenarios of Figures 3.7 and 3.8 provide insights into how the five scenarios (baseline, announced type 1 and 2, 2ºC, and 1.5 ºC Scenarios) might influence future temperature levels. Simulations show that reducing emissions results in lower temperatures compared to scenarios where emissions continue to rise at the baseline scenarios. The extent of reduction significantly influences the simulated temperature outcomes, with more substantial reductions of 0.9, 2.5, and 6% having a more pronounced impact on limiting global temperature increase to 2.62, 2.0, and 1.5ºC, respectively. In all the scenarios, the temperature rises from 2023 till 2100. However, the average annual temperature growth rate is different, with 1.15, 1.04, 0.84, 0.50, and 0.12% for the baseline, announced type 1 and 2, 2ºC, and 1.5ºC scenarios, respectively.

Similarly, the average annual emissions reduction growth rate is -0.09, 0.50, 0.90, 2.28, and 4.12%, respectively. The baseline scenario has a negative emissions reduction growth rate, which implies that emissions may continually be on the increase. Emissions are expected to peak between the year 2070 – 2080 owing to the envisaged world's population peak at that time too, hence, there may be reduced need for high energy usage in the building and other sectors, resulting in less emissions. Ideally, the output of the average annual emissions reduction growth rate, in particular the announced 2, 2ºC, and 1.5ºC scenarios, are supposed to be equal to the input emission reduction commitment per annum of 0.9, 2.5, and 6%, respectively. However, this is not the case with the simulation results as the model considers other factors, such as the population-economic growth dynamics of countries. Also, the world economic growth measured in annual GDP growth rate is expected to decrease, based on the OECD data for real GDP forecast [220]. The economies of industrialized nations like China are expected to peak, while those of the developing nations would continue to rise as they transition into being industrialized, and with more accessibility to electricity for all population. These dynamics resulted in discrepancies between emission reduction commitment and the output of the average annual emissions reduction growth rate in the announced 2, 2ºC, and 1.5 ºC scenarios. The cost of delaying the decision to reduce emissions is not to be overlooked, as the consequences outweigh the immediate cost of action.

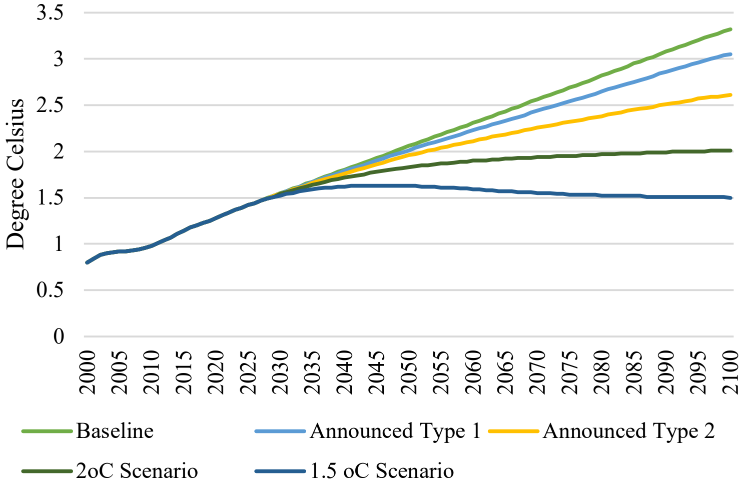


**Figure 3.7.** Different simulated policies versus global temperature rise

Given a short time interval between 2023 and 2030, the average annual temperature growth rates are 1.76, 1.67, 1.67, 1.67, and 1.48%, while the average annual emissions reduction growth rates are 0.03, 0.06, 0.17, 0.43% for the baseline, announced type 1 and 2, 2°C, and 1.5 °C Scenarios, respectively. The percentage changes within a short time series appear very little compared with the case of the long-term difference, even with the large emission reduction commitments. This outcome is in line with the work by L. A. Gil-Alana [204], which has shown that global temperature changes are hardly noticeable until a long-term span. The degree of uncertainty in determining how much temperature rise can be ascertained in the short term is owing to many variables that result in these changes. Some of these variables could be attributed to various factors like carbon cycle dynamics, complex interactions, and other uncertainties such as future human behaviour in terms of the release of anthropogenic gases (GHG), technological advancements, and natural system responses. Overall, simulations consistently show that reducing emissions is crucial for mitigating global temperature rise, with even moderate reductions of 0.9% in the announced type 1 scenario slowing the pace of temperature rise.

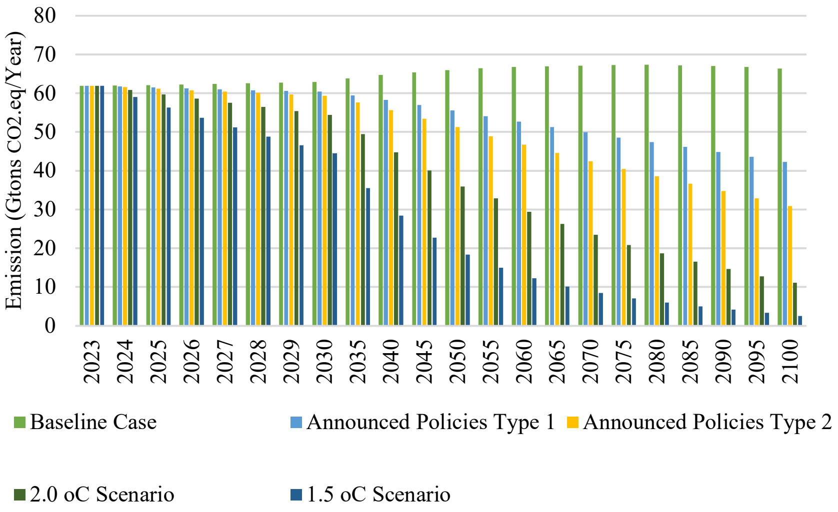
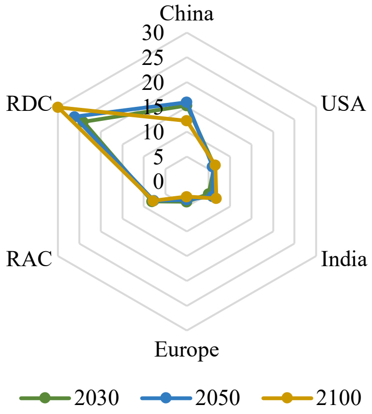


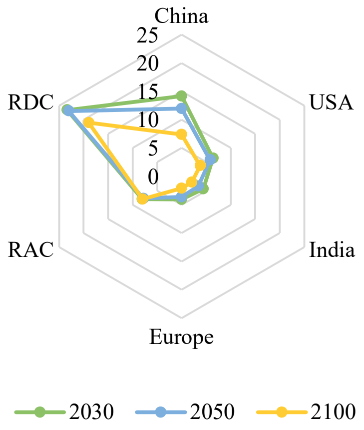
**Figure 3.8.** Different simulated policies versus emission

Figure 3.9 shows the results of all five scenarios in the years 2030, 2050, and 2100 for the different countries and regions where the commitments were made. In the baseline scenario of Figure 3.9 (a), only the EU shows emission reduction to 4.06, 3,63, and 3,03 Gtons CO$_2$ eq in the years 2030, 2050, and 2100, respectively. China showed a continuous increase to 15.98 Gtons CO$_2$ eq in 2050 from the 15.29 Gtons CO$_2$ eq value of 2030, with a corresponding reduction to 12.25 Gtons CO$_2$ eq by 2100. The rest of the advanced countries showed a value of 8.4 and 7.67 Gtons $CO_2$ eq in 2030 and 2050, respectively, with an increase to 7.76 Gtons $CO_2$ eq by 2100. For the USA, India, and the rest of developing countries, emissions value continually increased across the baseline scenario.

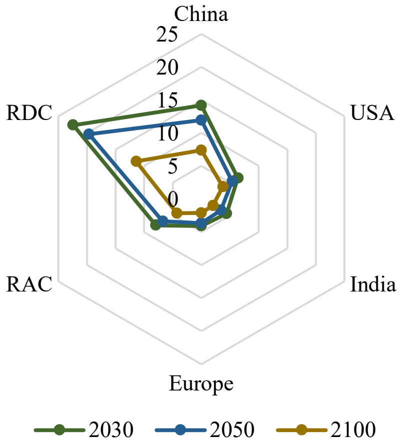
In the rest of the other four scenarios, as in Figure 3.9 (b) - (d), all six regions show progress in emissions reduction due to the introduction of policies to support emissions reduction. However, the results show an envisaged high growth in emissions value of the rest of developing countries. This change is an indication of the anticipated high growth in industrialization and increase in energy accessibility across developing countries, being a part of the UN Sustainable Development Goal 7 of providing clean and modern energy for all. Though substantial progress has been made in this regard, there is still a huge gap in the population's access to electricity in developing countries. For instance, only about 60% of Africa's population has access to electricity [90], and yet, there is also an increasing population growth compared with other regions or nations [221]. Therefore, in closing this gap while reducing the probability of high emissions from this form of industrialization, energy from renewable sources should be highly utilized, as this would drastically reduce further emissions from the power sector. Mitra S. et al. [222] emphasized the importance of such energies to be affordable towards increasing universal accessibility. The issues and challenges to achieving these are numerous and diverse, with the key ones being discussed by Akpan J. et al. in [26] and Batinge B. et al. in [223], providing a roadmap for reducing energy poverty in African electricity markets.



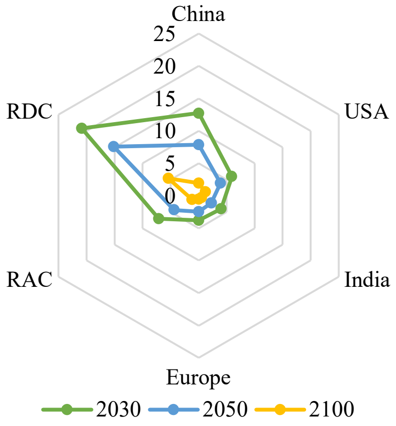
(a) Baseline Scenario



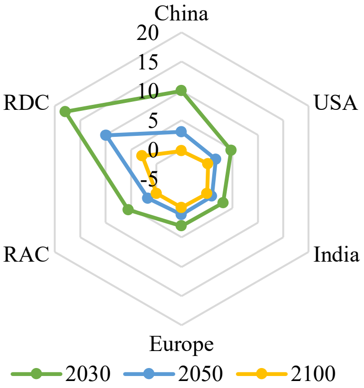
(b) Announced Policy Type 1



(c) Announced Policy Type 2



(d) 2.0 $^{o}$C Scenario



(e) 1.5 ºC Scenario

**Figure 3.9.** Summary of emissions (GTons $CO_2$ eq) at strategic period across countries/regions' (All Scenarios).

Consequently, considering climate justice, the National Determined Contribution (NDC) initiative proposed during COP26 is left in the hands of each country to determine its contribution to the global value in the drive to meet the UN SDG 2030 target. The results from sections 6.1 and 6.2 indicate that in the baseline case, the announced policies, types 1 and 2, are insufficient to mitigate global warming and climate change effects. Whereas, in the other two scenarios (i.e., 1.5 ºC and 2.0 ºC Scenarios), the world needs to increase its current NDC of emissions reduction by about 6.5% and 2.5%, respectively and concurrently across the 6 regions used in the hypothesis of this study as defined in the appendix, Table A1. In this way, reduction commitments can be. However, this measure is not without a challenge. The next section presents a discussion on this constraint and then proposes potential pathways that could help overcome the challenge with the strategy of equal percentage reduction commitment.

### *3.8.2 The Way-Forward*

The recent turnout from each country for the submission of her NDC has been poor; for instance, to reduce emissions in accordance with the Paris Agreement, ten nations updated their Nationally Determined Contributions (NDCs) in 2022. Of the 195 nations that have ratified the Paris Agreement, just about 30 have nevertheless set clear goals for achieving net-zero emissions [91]. While regulatory policy announcements remained the same, there were around 80 new renewable energy programmes made on the demand side. Eight announcements came from Latin America and the Caribbean, seven from Asia, four from Africa, two from Oceania, and just one each from North America, the Middle East, and North Africa. Most announcements came from Europe. At the end of the year 2022, 94 countries either had goals or policies in at least one end-use sector, but only three (Spain, Portugal, and Turkey) had plans or objectives in all four end-use categories [91].

It is well understood that the complexity of ascertaining NDC is high, as it requires many sectors' inputs and data. For many countries, arriving at this data that presents the peculiar situation of the country is more cumbersome and would also involve regulation of existing energy policies and regulatory frameworks. Commitment to research findings in preferring holistic pathways in addressing these current issues is very timely. It cannot be overemphasized, as many governments and international organizations are actively looking out for the best measures to mitigate the consequences of emissions by facilitating the 100% RE vision, UN SDG, and climate change agenda of 2030. Emissions under accounting and conflicts between mitigation and adaptation goals are also important to consider in planning as the magnitude of these emissions remains unconstrained. For instance, the model by Lesk C. et al. [224] estimates that adaptation-related interventions would reduce approximately 1.3 $GtCO_2$ through 2100, while the energy used to deploy renewable capacity should be larger.

Hence, accurate data and long-term estimates of energy demand, the need to create adaptable and responsive market and regulatory frameworks, international collaboration and coordinated activities are necessary strategies to decarbonize the current global systems. In this study, we emphasize fair sharing as an important consideration for developing strategic emissions reduction, energy, and climate policy for progressive achievements through planning and implementation. Hence leaving no room for prejudice in the sharing. For instance, this reduction measure employed in this study to achieve the 2.0 to 1.5 $^{o}$C scenarios was fairly shared among the regions and countries used in the simulation.

Suggested in Table 3.7 below are other possible areas that can help have a more responsive NDC needed to facilitate the rapid deceleration of global emissions increase and to stay within the right temperature rise threshold.

**Table 3.7.** The way forward towards reaching the 1.5$^{0}$C - 2.0$^{0}$C scenario.

| Concepts | Description of Proposed Pathway |
|---|---|
| Regional NDC Stock-Taking and Equally Shared Globally Determined Commitment (GDC) Concept | This initiative should be aimed at replacing the current pattern of NDC global stock-taking in a 5-year interval. Rather, stock-taking should be a 2-year interval carried out at the regional or continental level, at least twice before the main global forum. |

| | |
|---|---|
| | This way, countries' efforts are measured earlier, and appraisal for immediate support in the continuous reduction of emission synonymous with the requirements for the 1.5$^0$C - 2.0$^0$C Scenario is done well in time.<br>This initiative acknowledges the efforts of a few countries that have made the commitments. But because this commitment is made at the will of individual countries, there is bound to be a possibility of no prioritization of commitments. Therefore, finding the right emissions reduction sharing ratio that considers other factors such as developmental issues, renewable resource constraints, and the economic situation of developing countries is pertinent. |
| Reducing the $CO_2$ emissions per wealth class per population | The wealthiest individuals and highest-income nations produce a disproportionate amount of the world's $CO_2$ emissions. In order to reduce emissions, both high-income individuals and rapidly expanding places should be the focus, with each group's unique challenges and opportunities being carefully taken into account. This initiative should be driven by a global effort that takes these complex dynamic issues, such as behavioural changes in the emissions disparities, into account to ensure a just and fair decrease in $CO_2$ emissions. |
| Equality with the Drivers of Climate Change Acts and Decisions | This initiative is poised towards the inclusiveness and even appropriation of global climate decision makers, as most key representation of climate change decisions is made from a selected few and from countries not representing full global coverage representation. |
| Emissions Budgeting Framework for Attractiveness of Investment Towards 1.5$^o$C | In order to meet the 1.5°C objective and reduce global emissions, a huge financial investment commitment is required.<br>In addition to government and public support, private investment is highly required. To ensure that financial commitment in this region is attractive, an Emissions Budgeting Framework is important.<br>This budgeting framework should allow the predictability of Carbon emissions cost per investment options, mitigate high-carbon asset risks, align with global climate goals, and induce green capital through carbon pricing and tax incentives. Organizations can commit to decarbonization since clean technology investment and climate action are promoted via low-carbon technology innovation. Hence promoting social and environmental responsibility as well as increasing stakeholders and public support. With this approach, the investing community can help create a more sustainable and climate-resilient future. |

In addition, the claims in [225], [226] show that Africa generally has historically had a small impact on global warming in terms of countries' contribution to global $CO_2$ and GHG emissions. But these assertions cannot be used to justify continuing to pollute at current rates for these countries. Why? Because the consequence effect does not exclude fewer $CO_2$ emitters, as the impact can be direct or indirect. Africa today can make huge technological leaps that would contribute to flattening the curves to net-zero emissions by pushing into policies, research, and implementation of projects from renewable energy sources to meet each country's electricity consumption.

The EU NDC commitment, done at a regional level [227], with noticeable progress even with the advent of the recent Russia – Ukraine war that kept the EU's energy dependence on imports at a disadvantaged position, proves the resiliency of the EU towards the NDC emissions goal. The EU has had a joint effort to reduce GHG emissions, being evidenced in their NDC proposal. In the coming years, the bulk of the emission is envisaged to come from developing countries due to the anticipated increase in energy access by the population and the growing industrialisation agenda.

Therefore, it is pertinent to consider ways of both managing and mitigating this emission through a determined commitment at a centralised level. The current NDCs are done in a decentralised pattern, leaving the individual countries with a wavering will and dwindling decision over the implementation of announced strategies.

From the perspective of this study, it is believed that the most effective way of reducing emissions without impeding other developmental agendas could be best done through a just, fair approach yet at a regional commitment level. Furthermore, most developing countries are energy poverty-driven yet full of one of the world's largest renewable energy resources; therefore, in the commitment to reaching the 1.5°C scenario, this inequality in energy access should be accounted for in any further NDC commitment, proposed pathways in Table 15, and climate science models, as these are often overlooked in many existing frameworks. Hence, this study emphasises the unity in diversity towards reducing emissions burden and mitigating climate change.

## 3.9 Conclusion

There is a lot of technical and political depth to the current conversation on how to evaluate a country's NDC progress towards the 1.5°C scenario. This complexity makes it challenging to have a central consensus on the “right" or "objective" technique to follow. Many models and climate systems have been developed to provide platforms to determine the effects of the current practices on global warming and climate change. The challenges with the complexity of these existing tools have been supported by the introduction of feedback loops to allow for the simulation of the different actions that can either enhance or mitigate the impacts of climate change. In this study's simulations, feedback processes are incorporated in the simulation tool used, which accounts for uncertainties already established by existing complex integrated assessment models. The process involves studying variables such as greenhouse gas emissions, energy consumption patterns, technological deployment, land use changes, and policy adoption. Key components include implementing significant reductions in greenhouse gas emissions, transitioning to sustainable energy sources, implementing renewable energy infrastructure, and implementing carbon reduction technologies. All these processes were assumed to have been accounted for in the NDC reduction percentages used in this study. The model considers data from historical emissions, current NDC commitments, technological advancements, and socio-economic factors.

The findings from this study promote the initiatives of the Intergovernmental Panel on Climate Change (IPCC) reports to keep the global temperature level below 1.5ºC and suggest that the comprehensive adoption and serious commitment towards NDCs of reducing emissions at about 2.5 and 6.0% can significantly mitigate global temperature rise to 2.0ºC and 1.5ºC, respectively as against the current practices. The overall results produced projections of Earth's climate responses to temperature changes. Figures 3.7, based on the emissions values at the strategic periods, as shown in Figures 3.8 and 3.9 (a) – (e) from each policy scenario, respectively, could help governments, corporations, and communities make informed decisions regarding mitigation techniques, adaptation measures, and policies to limit global temperature rise to 1.5ºC. The findings and perspectives presented in section 3.5.1, with the proposed pathways in Table 3.7, provide valuable insights for policymakers, stakeholders, and the broader scientific community, offering a strategic framework for improving NDCs, fostering international collaboration, and bolstering global commitment to tackling climate change complexities.

# Chapter 4

## Towards the 1.5°C climate scenario – the Economic Model

Published as: Akpan J., Olanrewaju O. (2023) "A Novel Evaluation Approach for Emissions Mitigation Planning and Budgeting Towards the 1.5°C and Alternative Scenarios".
Journal: Atmosphere [228].

## 4.1 Introduction

### *4.1.1 Background*

The Earth's climate is experiencing rapid and unprecedented changes due to human activities, particularly greenhouse gas emissions. The international community, through the Paris Agreement, has set ambitious targets to mitigate climate change, aiming to limit global warming to well below 2°C above pre-industrial levels. Achieving the 1.5°C climate scenario is recognised as a critical threshold to avoid catastrophic climate impacts; hence, the urgency of addressing climate change cannot be overstated. The world stands at a critical juncture in our history, where the choices of financial investment made today will not only profoundly impact the future of our planet but could create eco-friendly avenues for sustained jobs and high returns on investment. Targets for reducing emissions and the measures to implement them have traditionally been at the centre of efforts to mitigate climate change. However, the monetary considerations in research towards the 1.5°C climate scenario are often overlooked and have only recently gained momentum in international bodies in charge of climate change and sustainable development because of the crucial position of financial viability to the success of such climate change [57], [229], [230]. These successes have been shown by new global shreds of evidence in [148] of the contribution of climate finance to environmental sustainability. Zhang L. et al. [146] also used panel data between 1990 to 2020 for China to show that green finance and financial inclusion have largely contributed to the promotion of renewable energy efficiency through technological innovation needed to decarbonise China. The study by Zhang D. in [231] shows that while economic development, energy consumption, trade, and foreign direct investment all lead to a rise in $CO_2$ emissions in G-20 economies, green finance and digital finance can lower those emissions. Policymakers and private sectors should support digital and green financing, as well as establish a market for carbon pricing and budgeting framework to support sustainable development [65], [231].

Emissions cost mitigation planning and budgeting as cornerstones of the climate action agenda are pertinent towards a low-carbon, sustainable future. Therefore, models, frameworks and strategies for emissions mitigation planning and Carbon budgeting are needed. Several existing climate models, pathways and mitigation strategies, such as the ones in ref. [56], [148], [232], [233] acknowledge that reducing emissions are with very many environmental benefits, such as keeping the global temperatures and sea levels from rising, maintaining the best weather events, fewer disruptions to the environment ecosystems, and less threat to the well-being of our planet and its inhabitants. Long-term national-level scenarios need to be evaluated so that the effects of these actions on reaching these goals may be understood. Dhar S. et al. [234] identified that there are currently few studies that use long-term scenario modelling at the national level to examine the effects of Nationally Determined Contributions (NDCs) and the necessary follow-up measures. Existing climate models with long-term scenarios, such as the ones listed in [214], have attempted to integrate NDC in their model scenarios but hardly discuss the intricacies of the economic benefits of achieving climate targets such as the 1.5°C scenario. Also, these models are scarcely able to explain a direct relationship between the financial need and the climate scenarios but often perceive the financial requirements as too ambitious as it is often talked about in public discourse. The first significant difficulty appears to be developing a thorough analytical framework to evaluate financial viability and the possible impact of climate change and the low-carbon transition [235], as climate change has been identified as the new source of risk for financial system [236], with few studies considering examination of the risk and benefits of climate change on transition finance.

### *4.1.2 Novelty of the Economic Model and Chapter Contribution*

This chapter seeks to address these challenges by providing a quantifiable model that allows for the discussion of the economic financial benefits of transitioning towards 1.5°C both at the global and national levels. The model is a simplified framework that uses the financial requirement of different investment policy options or scenarios through emissions cost mitigation applications derived from cost-benefit analysis concepts. To the best of my knowledge, the approach used in this Chapter has not been found in the literature. Therefore, this research represents an essential step of contribution to the body of knowledge towards ensuring that our efforts to mitigate emissions under the desired climate scenarios are not seen as being only ambitious but also attractive, strategic, adaptable, and equitable.

The journey towards the 1.5°C climate scenario, the run-up to COP 28, and a planned follow-up with the first global stock-taking appears complex and with multifaceted challenges. It is the hope that this research contributes to a deeper understanding of the path forward and guides policymakers towards a more sustainable and resilient emissions budgeting plan that explains in a simplified manner the economic attractiveness of policy decisions to investors. By reviewing and analysing the recent literature and policies, a foundation is laid as a groundwork for the framework developed in this study. This model can guide decision-makers and or private bodies in setting robust and effective emission reduction targets, as well as a realistic budget emissions mitigation towards having a global Carbon budget that supports the right global temperature levels.

### *4.1.3 Structure of the Chapter*

This chapter is structured into nine sections: the introduction of the study, followed by a literature review covering the overview of emissions mitigation planning and budgeting as the rationale behind the approach adopted in this study. In the third section, the methodology is explained together with the modelling process and the data input computation. The results are presented in the fourth, fifth, and sixth sections, where the findings for the first set of policy scenarios, followed by the validation of the model after the application of the model on illustrative cases of China, USA, India, and the European Union (EU) in the sixth section. The seventh section shows the model validation, and in the eighth section, the discussions on policy implications of the findings using the time value of the policy scenario are made. Finally, the ninth seven concludes the work with model limitations and recommendations for the use of the simplified emissions budgeting model.

## 4.2 Review of Literatures

### *4.2.1 Emissions mitigation planning and budgeting – An Overview*

The concept of a global "carbon budget" (the total quantity of "allowable" carbon emissions to satisfy a goal of world temperature) is an important idea in climate science and policy. The study by B. Lahn in [237] examines the contributions to the literature on the carbon budget from the 1980s to the current day and finds that there have been three major revisions in how scientists see the policy importance of the carbon budget. Carbon budgets are a helpful framework for thinking about the climate mitigation challenge because they describe the total permissible $CO_2$ emissions linked with a certain global temperature target [238]. The relationship between carbon budgets and other policy-relevant variables can be better understood with the help of scenarios from integrated assessment models, which provide a comprehensive approach through many indicators on how quickly and how much emissions can be reduced. Some of the key indicators in the integrated assessment include what rate of decarbonisation, the predominance level of low-carbon technologies, and the year global emissions could peak. The global decarbonisation rate towards 1.5°C and other climate scenarios have been simulated in chapter 3 of this study, in line with several other forecasts that research findings and international energy reports such as the ones made in [230], [239], [240], [241], [242]. Low-carbon technologies are projected to contribute between 50% and 75% to scenarios with a budget below 1000 $GtCO_2$ by 2050, with a >66% chance of limiting global warming to below 2°C [243]. The carbon budget, determined by $CO_2$ emissions, can be explained according to [238] by the relation in equations 2.0 and 2.1 below.

$$e_c = \left[\frac{1}{\mathrm{E}_{tcr}}\right] \tag{2.0}$$

Where $e_c$ is the budgeted emissions, while $\mathrm{E}_{tcr}$ is the transient climate response to cumulative emissions, computed from observational data or Earth system models (ESMs) with a dynamic global carbon cycle and is represented by $\Delta \mathrm{E}/\mathrm{T}_{r}$.

$$\Delta \mathrm{E} * e_c = T_r \tag{2.1}$$

$\Delta \mathrm{E}$ is the cumulative emissions, while $\mathrm{T}_r$ is the global temperature rise over time. By reducing the cumulative emissions, the global temperature rise could be reduced as a direct relation, whereas an increase in the emissions moves the global temperature rise higher, as can be seen in Figure 4.1. The amount of carbon dioxide released into the atmosphere throughout the Industrial Revolution is directly correlated to the increase in global average temperature that occurred during that time [244].

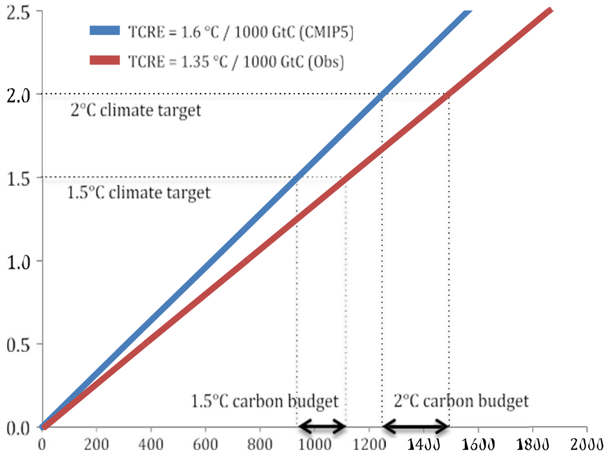


**Figure 4.1.** Comparison of two TCRE estimations' cumulative $CO_2$ emissions and $CO_2$-induced temperature change, according to H. D. Matthews *et al.* in [238].

The goal is to achieve zero net emissions, as per the Paris Agreement; since climate change's effects are already visible, low-technology energy must be employed to create fuels that could facilitate this need across all regions and countries. The Paris Agreement includes provisions for countries to establish their targets for decreasing emissions of greenhouse gases through mechanisms known as Nationally Determined Contributions (NDCs). These NDCs should be assessed for 'fairness' as part of a planned 'ratcheting-up' mechanism to guarantee they are in line with the larger aim of limiting the rise in world average temperature to far below 2°C or even 1.5°C.

Several studies that have analysed and proffered pathways for energy transitions with Carbon budgets have been investigated. The (C&C) concept distributes a global carbon budget across nations to keep emissions below 2°C and equalise per capita $CO_2$ emissions within decades [245]. Recent global carbon budget estimates—cumulative $CO_2$ emissions consistent with a certain degree of climatic warming—may strengthen climate mitigation policy dialogues to keep world temperatures within the 1.5 - 2°C range. However, this presents significant problems regarding how to distribute this carbon budget across nations to respect the finite cap on overall emissions and solve the underlying disparities across states in their history and future emissions. The inadequacies of the egalitarian, responsibility-based, right-based, and capability-based models of carbon budget sharing that have gained popularity in recent decades are highlighted by this study [245]. The rate of progress towards sustainable development goals by individual nations has been used as the major comparable indicator in an endeavour to distribute the global carbon budget fairly. Along with these factors and the climate action of each nation, Rawls' idea of justice is applied to the allocation of the carbon budget [245]. The fair carbon budget share (FCB) model is a novel, dynamic, and prospective mechanism that is required for the annual distribution of countries' carbon budget shares. From the studies, there were large discrepancies between countries' actual carbon emissions and their fair share in both 2017 and 2018, and the shares determined using FCB were very different from the shares generated using the egalitarian method. The 2017 fair share, which revealed a solid equilibrium between debtor and creditor countries in relation to their actual greenhouse gas emissions, demonstrated that a market system can be prepared for implementation by the FCB model. Lee C. et al. [246] used the contraction and convergence C&C method to show that a country's cumulative carbon debt (or credit) is its past emissions compared to its share of the world population. This carbon debt/credit method simplifies setting national climate mitigation targets that account for past obligations and respect international equity in future emissions permits among countries. An equitable approach to allocating the global carbon budget is explored in the article [247]. The paper makes a distinction between "entitlements to carbon space" and "physically available carbon space," which is not always the case in previous treatments. All countries can apply the same mitigation strategy owing to the carbon budget approach detailed here. This method clearly operationalises the notion of "equity and common but differentiated responsibilities and respective capabilities" to achieve climate goals [247]. This research by N. J. van den Berg et al. [202] assessed the feasibility of applying these criteria of fairness and equity to the formulation of national emission targets and carbon budgets. It found that industrialised nations may end up with (large) negative remaining carbon budgets, which can be achieved using either the equal cumulative per capita or the greenhouse development rights approach. All effort-sharing options for industrialised countries lead to more stringent budgets than cost-optimal budgets, and cost-optimal processes do not lead to outcomes that can be defined as fair. The Paris Agreement has led to the EU's 'Fit for 55' policy package, which includes ambitious strategies for reducing greenhouse gases (GHG) in all economic sectors. However, the issue of whether the planned policies are sufficient to keep global warming below 1.5 °C remains unresolved. The research calculates transport GHG budgets throughout the EU27 and obtains European GHG reduction plans sufficient for a 1.5 °C rise in global temperature. The analysis indicates that the "Fit for 55" campaign of the transport sector is not yet as ambitious as necessary to accommodate a 1.5 °C scenario [203]. In the study by O. Alcaraz et al. [152], 15 countries currently at the top of the global emissions ranking were studied. Initial investigation has revealed that only the intended nationally determined contributions (INDCs) of these 15 countries are assumed to release into the atmosphere 84% of the GCB between 2011 and 2030 and 40% of the GCB between now and the end of the century. A first attempt to use the System Dynamics–based FML Model to generate city-level $CO_2$ emission numbers for cities of varied sizes in Malaysia was carried out by [26]. Carbon dioxide emissions are generally on the rise, correlated with population and GDP [50]. To determine a city's carbon budget, W. K. Fong et al. in [248] proposed three methods: equal share, population, and gross domestic product. The current model can accurately forecast historical, current, and future levels of carbon dioxide emissions from cities. Developing a national database of city-level $CO_2$ emissions is one example of how this method could be used in Malaysia and other developing countries. Carbon pricing is essential for high-penetration renewables to be economically viable. For instance, B. Elliston et al. [249], Elliston determined that a price on Carbon was necessary for a completely renewable portfolio. A carbon price of \$50–\$65 per metric ton of $CO_2$ equivalent ($MTCO_2eq$) is required for a 5% discount rate. A carbon price of \$100-\$70/MT$CO_2$e would be required if the discount rate were raised to 10%. Replacement of older fossil-fuelled generators with newer fossil-fuelled ones is economically desirable when carbon costs are below this level [249]. Other estimates of the carbon budget were examined by M. Dickau et al. [232]. It focuses on outlining significant uncertainties and evaluating their implications for climate policy and net-zero $CO_2$ targets. It suggests being upfront about the degree of uncertainty surrounding carbon budget forecasts and suggests that these goals should be updated frequently. The idea is well suited for guiding climate policy and determining if net-zero $CO_2$ targets are consistent with the goals of the Paris Agreement, according to new research into the carbon budget's level of uncertainty. Despite these difficulties, the notion is still worth considering. When considering that the world must be $CO_2$ neutral by 2050 to achieve the 1.5 °C goal, the average amount of the global carbon budget used up by 2030 should not be more than 55 per cent [50]. To keep global warming below a set threshold, scientists have calculated a "Global Carbon Budget," or GCB. The empty GCB represents all of humanity's historical emissions, most of which came from industrialised nations. The remaining GCB is the sum of $CO_2$ emissions that can be made without risking a rise in the global average temperature above a predetermined threshold. The AR6 forecasts that, as of the beginning of 2020, 400 Gt$CO_2$ is the remaining GCB that is consistent with the Paris Agreement (PA) goal of limiting the global temperature increase to 1.5 °C [50]. This estimate is said to be more than 60% accurate [50]. To what extent a country uses its leftover GCB to implement its NDC and LT-LEDS is a key factor in determining the country's national climate equity viewpoint [244]. Once a carbon budget is known, the marginal abatement cost MAC (i.e., the cost needed to reduce a unit of $CO_2$/ton of emissions) can be estimated. Marginal abatement costs play an important role in the allocation of emission reduction allowances and the planning of emission mitigation [250], [251].

Several works, with a selected few as the ones in Table 4.1, have dealt with the marginal abatement cost of emissions for different countries, with some aligning their investigations with different climate scenarios.

**Table 4.1.** Related Emissions mitigation planning and budgeting across selected countries and regions. Source: authors' elaboration.

| Country | Study Summary | Method | Key Indicators | Climate Scenario | Ref |
|---|---|---|---|---|---|
| World | Emissions mitigation costs and their determinants were studied. The results showed that energy consumption, financial crisis, $CO_2$ emissions rate, | Gravity model & quadratic directional output distance function | MAC | No | [252] |

| | | | | | |
|---|---|---|---|---|---|
| (for 41 regions, including 165 countries) | and GDP were great determinants and that as the globe's $CO_2$ emission continues to rise due to increasing GDP, reducing emissions is becoming more expensive | | | | |
| Global | The different MAC methods used in climate change policy to evaluate alternatives and costs were comprehensively reviewed. The study classifies MAC techniques and presents an applicability path analysis for the estimation of MAC. The study suggests that complex methods may not always be better than simplified ones, and MAC could be more reliable by ranking the relative value of options. | Review | MAC | Yes | [253] |
| Global | The projected annual abatement costs of achieving national climate plans (NDCs) were estimated based on domestic action, land, land use change and forestry (LULUCF) exclusion. The result showed conditions varying significantly across countries and achieving 2°C being more expensive. | IMAGE integrated assessment model | MAC | Yes | [254] |
| China | A low-cost path for China to peak its carbon emissions was explored. For each region before 2030, it calculates carbon emission efficiency and marginal carbon abatement cost using the parametric directional distance function. Rapid economic expansion increases marginal abatement costs, with developed areas sustaining development patterns and central and western regions adopting emission reduction responsibilities. The work stresses that the current emissions reduction path may yield an increasing MAC in the future. | Parametric directional distance function | Carbon emission efficiency and MAC | No | [255] |
| China (441 industries) | The correlation between MAC and carbon intensity varies among industries, with energy-intensive industries showing a significant S-shaped relationship. | Functional data analysis | MAC, Carbon intensity | No | [256] |
| China and India | The costs and benefits of India's and China's NDCs were compared. It found that India's original carbon MACCs are generally higher than China's, but revised MACCs are slightly higher. Yet, India | Computable general equilibrium model | MAC and CB | Only NDC Scenario | [257] |

| | | | | | |
|---|---|---|---|---|---|
| | has more significant cost-saving effects, while China faces difficulties in reducing emissions. | | | | |
| India | The study compares India's National Development Goals (NDC) and global temperature stabilization targets, finding significant emissions disparities. Delaying abatement measures could increase mitigation costs. | Computable general equilibrium model | MAC | Yes | [258] |
| USA | The study examines the US climate policy's costs and benefits, focusing on $CO_2$ emissions levies and tax relief. Co-benefit values vary from \$150-1250 per household, while policy costs average less than 0.5%, demonstrating significant heterogeneity across space and income. The research shows a marginal welfare cost and co-benefit of \$31/t$CO_2$ and a climate benefit of \$27/t$CO_2$ or less to justify a \$25/t$CO_2$ tax rise at 5%. | Computable general equilibrium model | MAC and CB | Yes | [259] |
| USA | The results showed that zero-carbon US electricity infrastructure would incur additional MAC, which can be reduced by employing low-carbon resources, and technologies with negative emissions show a financial benefit. | Sequential optimization model | MAC | Yes | [260] |
| EU | The paper uses a to analyse least-cost GHG emission abatement pathways in EU countries. A correlation was established between 2030 abatement objectives of varying ambition and a country's probability of accomplishing a strong 2050 aim. | Constrained optimization model | Emission target, MAC | Only NDC Scenario | [261] |
| US, EU, China, and India, | According to the study's hypothesis, nations with relatively low marginal costs of carbon emissions could end up paying an enormous cost to combat climate change. The analysis estimates the total and marginal costs of abatement for the US, EU, China, and India based on the outcomes of the 22nd Energy Modelling Forum. | EMF-22 models | Emission target, MAC | Yes | [262] |
| EU | This study explores decarbonization possibilities that combine energy systems analysis with marginal abatement cost curves (MACs). The findings indicate that MACs rely on model assumptions, with bioenergy and CCS technology being important factors. Important mitigating | A novel analytical technique | Energy System Analysis, MAC | Only NDC Scenario | [263] |

| | | | | | |
|---|---|---|---|---|---|
| | actions are categorized into three groups: resilient, tipping-point, and niche. | | | | |
| Developing countries | This study examines developing nation emission goals, abatement costs, and energy use in 2020. The findings showed that by 2050, developing nations would have tougher emission objectives and higher abatement costs. | Integrated modelling framework FAIR | Emission targets, MAC, and energy consumption | Only NDC Scenario | [264] |
| World, China, EU, India, and the USA | This Chapter | Developed in the Study (a simplified parametric model approach) with input emissions data from the simulation results of the environment model as in Chapter 3 | MAC, NPV, CB, Avoided Emissions Cost Growth | Yes | This chapter |

### *4.2.2 Rationale of the Economic Model*

The research reviewed in section 4.2.1 and Table 4.1 has provided a foundation for understanding MAC and climate scenarios for countries and the world within the context of this Chapter. Most research in the literature is similar, while some are distinct from the ones highlighted in Table 4.1. Yet, they have hardly discussed the economic attractiveness of the climate scenarios in a quantifiable manner.

Given the marginal abatement cost, potential investment opportunities can be weighed [250], [251], forming the basis for possibly evaluating the attractiveness of potential investment options. Hence, this study uses a simplified MAC to estimate avoided and unavoided emissions cost (explained better in the next section, methodology) to guide in understanding the attractiveness and viability of each investment or policy choice towards reducing the GCB for countries/regions and the world under the climate scenarios. In determining the attractiveness of each policy scenario, the principle of capital budget is incorporated.

Generally, capital budgeting techniques (CBT) are used to determine the most attractive option for making investment decisions. CBT is often determined mainly through two categories; the first is based on discounting criteria constituting the net present value of investments NPV (value of investment at current time), internal rate of return IRR (return on investment), and profitability index PI (profit ratio for every unit of money spent). In contrast, the second is based on non-discounting criteria such as accounting rate of return

ARR (returns on investment after tax and depreciation) and payback period PBP (time to recover the investment). Figure 4.2 shows these categorisations. Since CBT is a planning choice, these indices affect both the predictability of the budget and the actual spending.

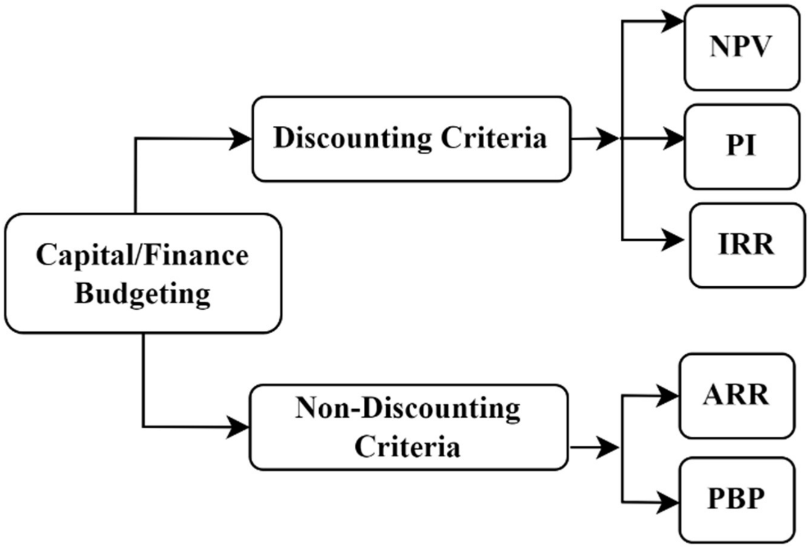


**Figure 4.2.** The general form of capital finance budgeting indices. Source: author's elaboration.

Capital Budgeting Techniques (CBTs) indices shown in Figure 4.2 have been extensively discussed and referenced in literature, some of which include the ones in [265], [266], [267], [268] and with a five-decade review on CBT by Sureka et al. in [265]. Pintarič, Z. et al. in [269] have emphasised the significance of understanding the application of CBTs. In contrast, Sureka et al. [265] have concurred that the utilisation of modern methods, such as the discounted cash flow (DCF), yields higher capital investment and eventually contributes to enhanced long-term profitability. It is generally accepted that the NPV is the favoured index among researchers since it measures the potential financial gain from selecting the best alternative [265]. The internal rate of return (IRR), despite NPV, is also used in business because it enables more detailed comparisons of projects of various sizes by utilising a single rate of return that is unaffected by the discount rate [265], and may become erroneous if the project is mutually exclusive [270]. In this study, NPV is preferred for use as each policy scenario begins with the same amount of emissions to be removed, and comparison is only made against the best-case scenario (i.e., the 1.5 ºC scenario). The discount rate is also varied based on the prevailing global inflation rates and or GDP growth in each investment scenario. CBT practices have been applied even at country levels, such as in China, Netherlands [271], Canada [272], Pakistan [273], USA [270], UK [274], and Korea [275] for improved decision-making.

Hence, in the illustrative application of the EB model in this study, we applied our framework to selected case countries that have been among the major global GHG emitters, i.e., China, the USA, India, and the EU.

Žižlavský in [267] demonstrated the potential financial value of the NPV method to the management of innovation projects. Pintarič, Z. et al. [269] stressed the importance of NPV as an economic criterion that can provide design compromise with intermediate efficiencies and impacts, such as environmental benefits, when profit consideration may be less attractive. When examining the time worth of money, sustainability net present value results from the trade-off between economic profitability, environmental (un)burdening, and social benefits like the creation of new jobs [268]. With the results that are obtained from the budgeting indices, an investment decision can be made by the following evaluation rules, shown in Table 4.2.

**Table 4.2.** Decision rules based outcome of budgeting indices

*RoR – Rate of Return

| S/N | Budgeting Indices (BI) | BI > 0 | BI = 0<br>BI = 1 | BI < 0 | BI > 0 (with all investment scenarios or options) |
|---|---|---|---|---|---|
| 1 | NPV | Accept investment | NPV = 0, no investment attractiveness | Reject investment | Rank investment options from highest to lowest BI value and choose the highest |
| 2 | PI | Accept investment | PI = 1, no investment attractiveness | Reject investment | Rank investment options from highest to lowest BI value and choose the highest |
| 3 | IRR | Accept investment | ARR = minimum required RoR, no investment attractiveness | Reject investment | Rank investment options from highest to lowest BI value and choose the highest |
| 4 | ARR | Accept investment | ARR = minimum required RoR, no investment attractiveness | Reject investment | Rank investment options from highest to lowest BI value and choose the highest |
| 5 | PBP | Accept investment | - | Reject investment | Rank investment options from highest to lowest BI value and choose the highest |

CBT practices have been applied even at organisations and country levels for improved decision-making. The summary of the findings from the use of CBT is presented in Table 4.3.

**Table 4.3.** Some Related CBT and Outcomes as Used in Selected Countries.

| Country/Organisation | CBT Indices | Summary | Implications of Findings | Ref |
|---|---|---|---|---|
| Fortune 1000 companies | NPV, PI, IRR, ARR, PBP, and other supplementary indices | The study compared the use of CBT for 1000 Fortune-rated companies and revealed that NPV was the most preferred tool compared with IRR, which had been often preferred in earlier years. | The findings indicate a better alignment between academic and business perspectives that had always debated the preference of one over the other. | [270] |
| China and Netherlands | NPV, IRR, ARR, and PBP | This article establishes a link between capital budgeting and economic growth. The authors claim that economic markets have made DCF approaches more useful, practical, and necessary, maximising shareholder value. The study tested this theory using 42 Dutch and 45 Chinese enterprises. | The primary findings were that Dutch CFOs utilise the NPV approach more than Chinese ones, employ ARR more, and estimate the cost of equity less often. IRR utilisation is similar in both nations. Further study and larger data sets are recommended for comprehension. | [271] |
| Canada | NPV, IRR, and Real Options | In this article, 88 big Canadian enterprises are surveyed by mail on CBT decision-making. The result shows that most corporations have NPV and IRR, whereas 17% do not use discounted cash flow (DCF). | The paper describes a theory-practice gap in DCF capital budgeting decision processes, suggesting increased attention to DCF. | [272] |
| Pakistan | NPV, IRR, and Real Options | The study used 200 firms listed on Pakistani's stock exchange to evaluate CBT use. The result showed that most firms employed DCF models favouring NPV over IRR. | The theory-practice gap was low. The study found that Pakistani firms scarcely use real option indices. | [273] |
| USA and Canada | NPV, PBP, IRR, ARR | The summary of the different studies from 392 firms in Europe showed that large-scale businesses and investments often adopt NPV more. | The use of CBT depends largely on the size of the organisation | [276] |
| Europe (France, Germany, Netherlands, and the UK) | NPV, PBP, IRR, ARR | The summary of the different studies from 313 firms in Europe showed that large-scale businesses and investments often adopt NPV more. | The use of CBT depends largely on the size of the organisation | [277] |
| Turkey | NPV, PBP, IRR, ARR | The study reveals that the NPV method is the most preferred capital budgeting method for Turkey's Top | The results emphasise fixed capital investments' significance across a range of industries, | [278] |

|  |  |  |  |  |
|---|---|---|---|---|
|  |  | 500 Industrial Enterprises when evaluating investment projects. | including employment, value-added goods, R&D, and manufacturing. |  |
| Cambodia | NPV, PBP, IRR, ARR | A study of CBT practices in 53 manufacturing companies in Cambodia found PB to be the most preferred method, followed by NPV, DPB, and ARR. | Companies with longer existence and higher capital investment are more likely to use NPV methods. | [279] |

The studies reviewed in Table 4.3 confirm the greatest acceptance of the use of DCF analysis techniques (most particularly the NPV method) for large investments. However, the choice and use of analysis techniques appear to be independent of the type of project being evaluated, with no significant difference between the use of techniques for strategic and non-strategic projects. Risk analysis techniques, such as sensitivity/scenario analysis, probability analysis, computer simulation, and beta analysis, are more often used for strategic projects, suggesting that strategic projects would require greater attention to risk issues [274]. Only two of the CBT practices explored across the studies reviewed in Table 4.3 have also attempted to incorporate scenario analysis to understand to assess the risk of investment decisions. For instance, the CBT practices study for the Fortune 1000 companies by Ryan P. and Glenn P. R. in [270], and that of the Pakistani firms by Mubashar A. and Bin Y. in [273] attempted the incorporation of scenario analysis.

Therefore, in addition to the scarcity of studies in the literature on the use of NPV and scenario analysis to evaluate capital investment decisions, an empirical analysis of direct integration and balance between strategic investment decisions and financial analysis approaches is pertinent.

Hence, in this study, the use of NPV is adopted and synthesised for the scenario analysis of different policy options aimed at mitigating emissions towards different climate scenarios at the global level and in four countries (i.e., China, the USA, the EU, and India). The methodology developed is described in the next section of this study, section 4.3.

## 4.3 Methodology

### *4.3.1 Overview*

The proposed simplified framework for performing the cost-benefit analysis is shown in Figure 4.3. The emissions datasets are forecasted against the climate policy scenarios based on the objective of Chapter 3 of this thesis. The CBA is then evaluated for all the climate policy scenarios by considering the framework of Figure 4.3, which is explained further through the Emissions Budgeting (EB) modelling process of Figure 4, assuming a combined dataset using a parameterized model developed in this Chapter in section 4.4.4 and 4.4.5. Additionally, this model calculates the economic attractiveness in terms of NPV, BI, and avoided emission growth rate among the climate policy scenarios, providing a better understanding of the time value of the policy. The results are then validated to establish the relationship between delayed policy economic attractiveness to allow for a more comprehensive understanding of the economic risk and benefits of climate policy options.

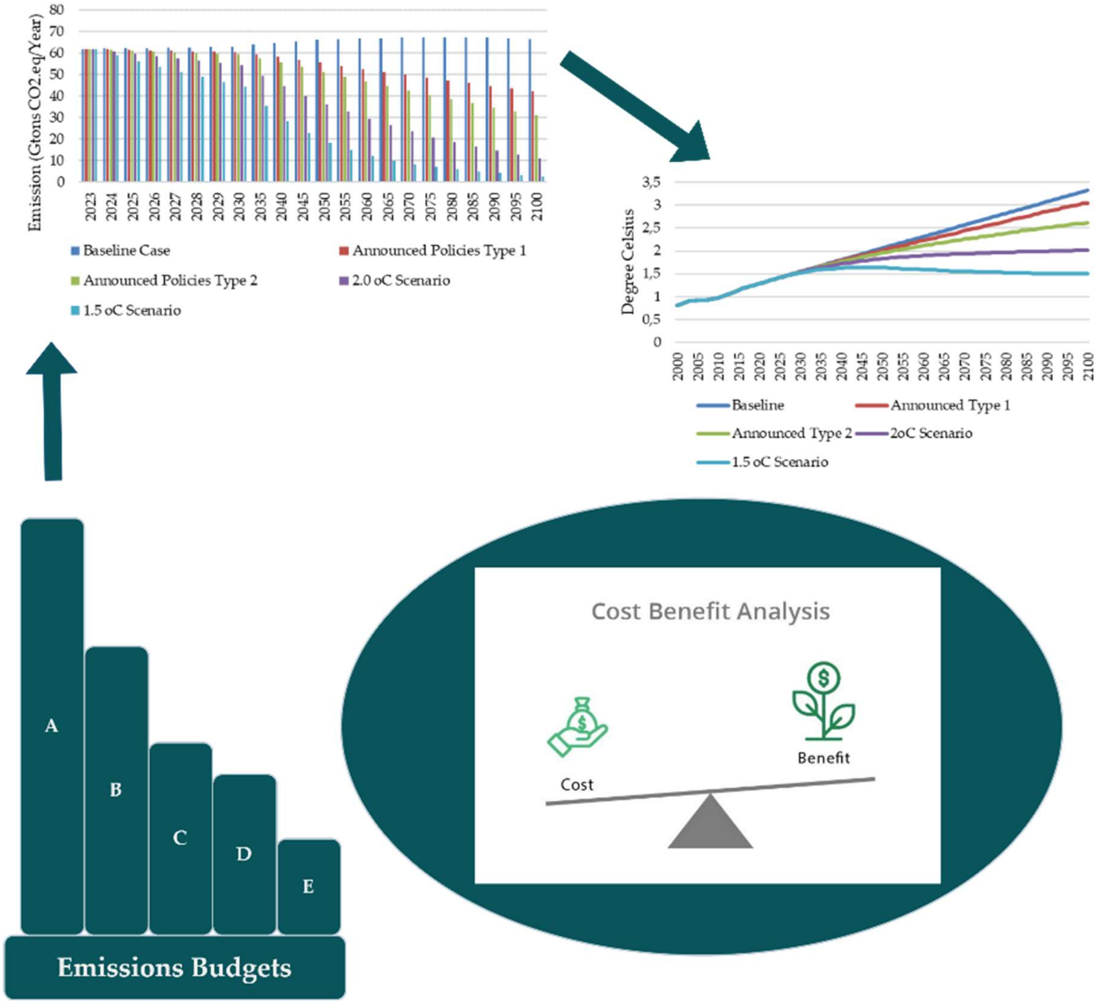


**Figure 4.3.** The framework of the simplified EB model for policy scenarios.

### *4.3.2 Model Inputs, Assumption, and Computation Strategy*

According to the global energy outlook by IRENA in [101], the current investment trajectory needs to be maintained through 2050 with an additional cumulative investment of USD 47 trillion to stay within the 1.5 $^{0}$C scenario. This sum is in addition to the USD

103 trillion in investments anticipated under the Planned Energy Scenario (herein, Announced Policies Type 2 in this study). In this part, both the Announced Policies Type 2 and the 1.5 $^{0}$C Scenario finance requirement were used to estimate the requirement for the other three scenarios, as shown in Figure 4.4 and with the financial requirements shown in Table A5 anf Figure A6.

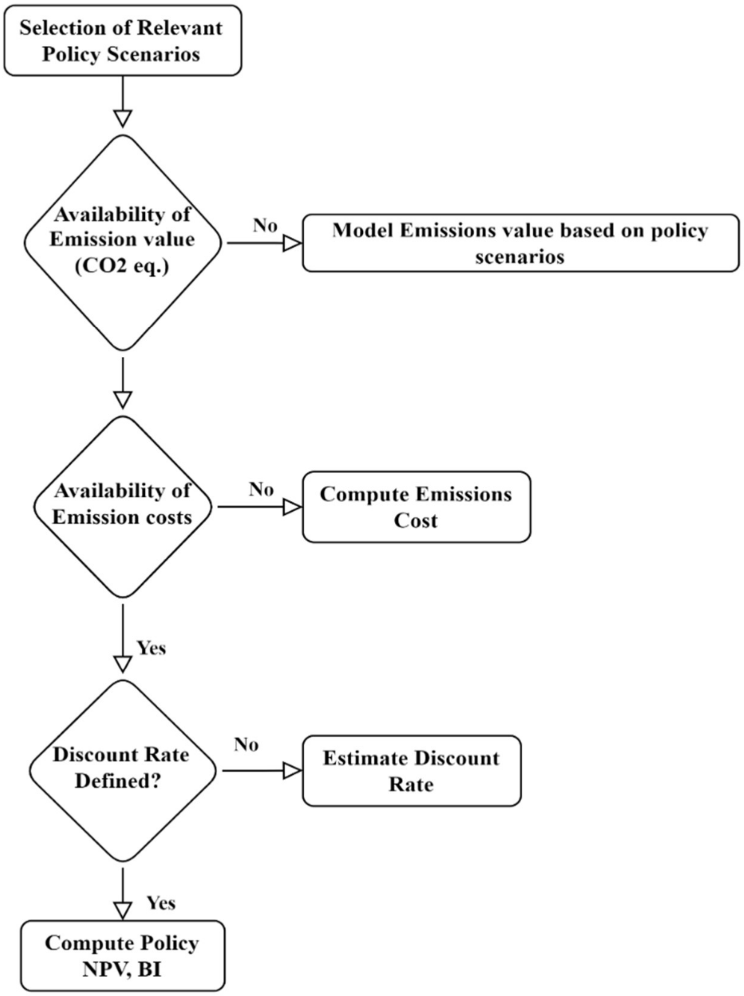


**Figure 4.4.** EB modelling process

The steps in modelling and key terms used are highlighted in Appendix Table A6 and A7, respectively. In the subsequent sections, use cases based on the policy scenarios of the preceding section are illustrated using the EB Model process flow of Figure 4.4. As was explained in the preceding section, the process behind the formulation of the EB model is represented in the framework of Figure 4.4 and explained further, with Table A5 having the key considerations used.

### 4.3.3 Selection of relevant policy scenarios and corresponding emissions

This chapter uses the different policy scenarios of Chapter 3, as shown in Table A2, to present the economic viability and value of each policy option. Hence, the emissions values of each policy have already been defined and accounted for. The other data sources are defined in Table A3 and A4, with corresponding rationale for the choices. The simulated climate policy scenarios from the preceding sections serve as the relevant policy scenarios for the CB analysis.

### 4.3.4 Categorisation and Monetisation of Emissions

The financial investment requirement cost set for the best-case simulated policy scenario (i.e., 1.5 ºC Scenario) serves as the base cost for comparison of benefits with other policy scenarios. In order to calculate the unit base emissions cost (i.e., the Marginal Abatement Cost), the following assumed relations in equations (2.2) – (2.5) are applied.

$$e_{bc} = \left[\frac{Ce_{1.5}}{e_i}\right] \tag{2.2}$$

Where $e_{bc}$ is the unit base cost of emissions removal (USD Trillion/Gtons $CO_2$.eq/Year), and $e_i$ is the initial $i$ emissions value (Gtons $CO_2$.eq/Year) at the start year of the policy. $Ce_{1.5}$ is the best case (i.e., 1.5°C Scenario) cost in USD Trillion.

Hence,

$$e_{bc} = \left[\frac{150}{61.98}\right] = 2.42 \tag{2.3}$$

Therefore, a unit of Gtons $CO_2$.eq represents 2.42 USD Trillion, which herein represents the financial requirement to remove 1 Gton of $CO_2$ eq. Emission. Notwithstanding the heterogeneity in the determination of the MAC option [250], a comprehensive review study on the applicability of MAC by Huang S. et al. [253] suggested that complex methods for MAC estimation may not always be superior to simplified ones, as policymakers must choose the right method for specific information needs. Hence, the study adopted the simplified equation (2.2) – (2.3) to estimate the unit base cost of emissions removal in order to determine the unavoided and avoided emissions cost (i.e., the present value of emissions reduction investment at a time t) and, in comparison, to the emissions cost from the other policy scenarios.

$$e_{uc} = 2.42 * \sum_{i=t} e_T \tag{2.4}$$

$$e_{ac} = Ce_{1.5} - e_{uc} \tag{2.5}$$

$$NPV = Ce_n + \frac{e_{ac1}}{(1+R)^1} + \frac{e_{ac2}}{(1+R)^2} + \frac{e_{ac}}{(1+R)^3} + \cdots + \frac{e_{acn}}{(1+R)^n} \tag{2.6}$$

Here, $e_{ac}$ is the avoided emissions cost for each n year, n = 1, 2, 3, …, 27 for (2023 – 2050). $Ce_n$ is the financial investment requirement for the number $n$ of different scenarios (i.e., baseline, announced type 1, announced type 2, 2.0°C, and 1.5°C Scenarios) cost in USD Trillion. These costs are presented in the Appendix, Figure A6, and Table A3.

Equations (2.4) and (2.5) were used to estimate and assign the monetary values as shown in the Appendix, Table A2 and A3.

Annual emissions flow and their monetary values are crucial to industrial and environmental economics and climate change policy analysis. They enable policymakers to evaluate the viability and consequences of climate policies by quantifying the economic costs and benefits of various policy options. This method is useful in pinpointing the best methods for reducing greenhouse gas emissions at the lowest possible cost. In this part, the economic impacts of various financial requirements and the resulting emissions values towards the 1.5°C are assessed by assigning monetary values of the climate policy scenarios. Similarly, as in section 3.2.3, equations (2.5) and (2.6) were employed to estimate and assign the unavoided and avoided emissions cost per policy at a time throughout the period used in the simulation. The unavoided and avoided emissions cost estimated are presented in the appendix, Table A2 and A3, respectively.

The relation of equation (2.7) is adapted from the concept of calculation of profitability index in cost-benefit analysis estimation, a measure of investment's attractiveness, often defined generally by equation (2.8) where NPV is the net present value of the capital for a selected investment option or financial requirement I.

$$Profitability\ Index = {}^{NPV}/_{I} \tag{2.7}$$

$$Profitability\ Index\ (I) \equiv Cost\ Benefit\ Index \tag{2.8}$$

$$I \equiv Ce_n$$

$$NPV = \sum_{t=1}^{n} \frac{e_{ac,t}}{(1+R)^t} \tag{2.9}$$

$$Cost\ Benefit\ Index\ (BI) = {NPV}/{Ce_n} \tag{2.10}$$

The Cost-Benefit Index (BI) is then determined by the computation of equations 2.9 and 2.10, where NPV is the net present value of a selected policy scenario, determined by the relation of avoided emissions cost and the emissions discounting rate, R over the investment period, t. This R-value (i.e., discount rate in capital budgeting) has no universal formula; rather, it can depend on the prevailing situation. For instance, high inflation rate, investment cycle, and a host of other factors. To be able to obtain R, the possible growth rate of GDP from the different investment scenarios was extracted from the input simulation GDP data of Chapter 3 for each policy scenario. An average GDP growth rate for the specified period of CB analysis was used as input for the discounting emissions cost flow rate calculated using equation (2.11) in this study.

$$GDP_{avr} = {1}/{N} * In\left[\frac{t_f}{t_i}\right] \tag{2.11}$$

Where N is the number of periods or simulation years, $t_f$ is the Average GDP growth rate at the last period/year, and $t_i$ is the initial year.

### *4.3.5 EB Model Fitness*

In Table 4.4, S1, S2, S3, S4, and S5 represent the values of the emissions cost discounting rate for the baseline, announced policy 1 and 2, 2.0°C, and 1.5°C Scenarios, respectively.

**Table 4.4.** Cases and assumptions for emissions cost discounting rate

| No. | Cases | Values (%) | References |
|---|---|---|---|
| 1 | Use of the initial emissions cost discounting rate used for the simulation of policies in previous study | S1 (2.29)<br>S2 (2.31)<br>S3 (2.33)<br>S4 (2.39)<br>S5 (2.48) | Calculation as per equation (2.11) |
| 2 | Increase in the emissions cost discounting rate of case 1 by 10% | S1 (2.52)<br>S2 (2.54)<br>S3 (2.57) | Calculation as per equation (2.11) |

| | | | |
|---|---|---|---|
| | | S4 (2.62) | |
| | | S5 (2.73) | |
| 3 | Increase in the emissions cost discounting rate of case 1 by 15% | S1 (2.64) | Calculation as per equation (2.11) |
| | | S2 (2.66) | |
| | | S3 (2.68) | |
| | | S4 (2.74) | |
| | | S5 (2.85) | |

The present chapter utilises equations 2.12 and 2.13 to assess and interpret the available data for use as emissions cost discounting rate (R), considering the anticipated that an increased global real gross domestic product (G) would result in R increase.

$$\frac{d}{dt} GDP_{avr} \propto R_S \qquad (2.12)$$

The symbol $\frac{d}{dt}$ represents the derivative of a $GDP_{avr}$ variable with respect to time in years. The equation demonstrates a positive correlation between the growth rate of GDP and the discount cost for emissions reduction per policy option S1 – S5, as indicated by the proportionality $\propto$.

$$\frac{d}{dt} GDP_{avr} = R_S \left(1 - \frac{R_S}{max(R_S)}\right) \qquad (2.13)$$

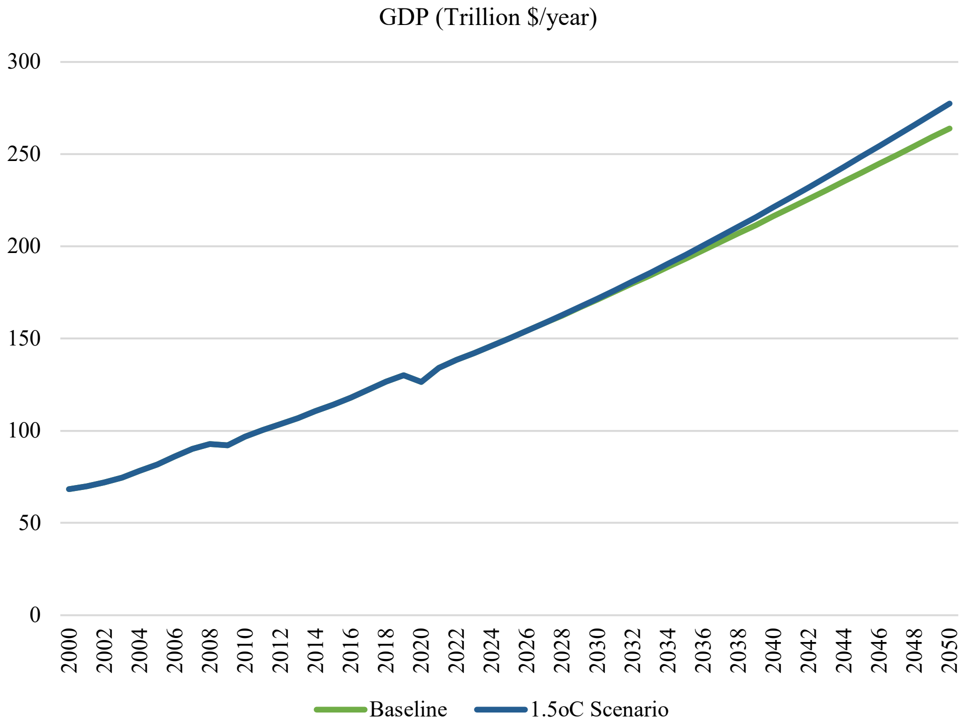
$R_S$ is expected to vary depending on the policy scenario S, but it cannot go above a specified limit max ($R_S$) = 3%, as the global GDP growth rate is forecasted to be between (2.5 – 3) % by 2050, according to the OECD data in [220]. Hence, only three cases are used in this study to keep the emissions cost discounting rate less than 3%, which is assumed with the GDP growth rate.

$$\frac{d}{dt} R_S \propto \frac{1}{NPV} \qquad (2.14)$$

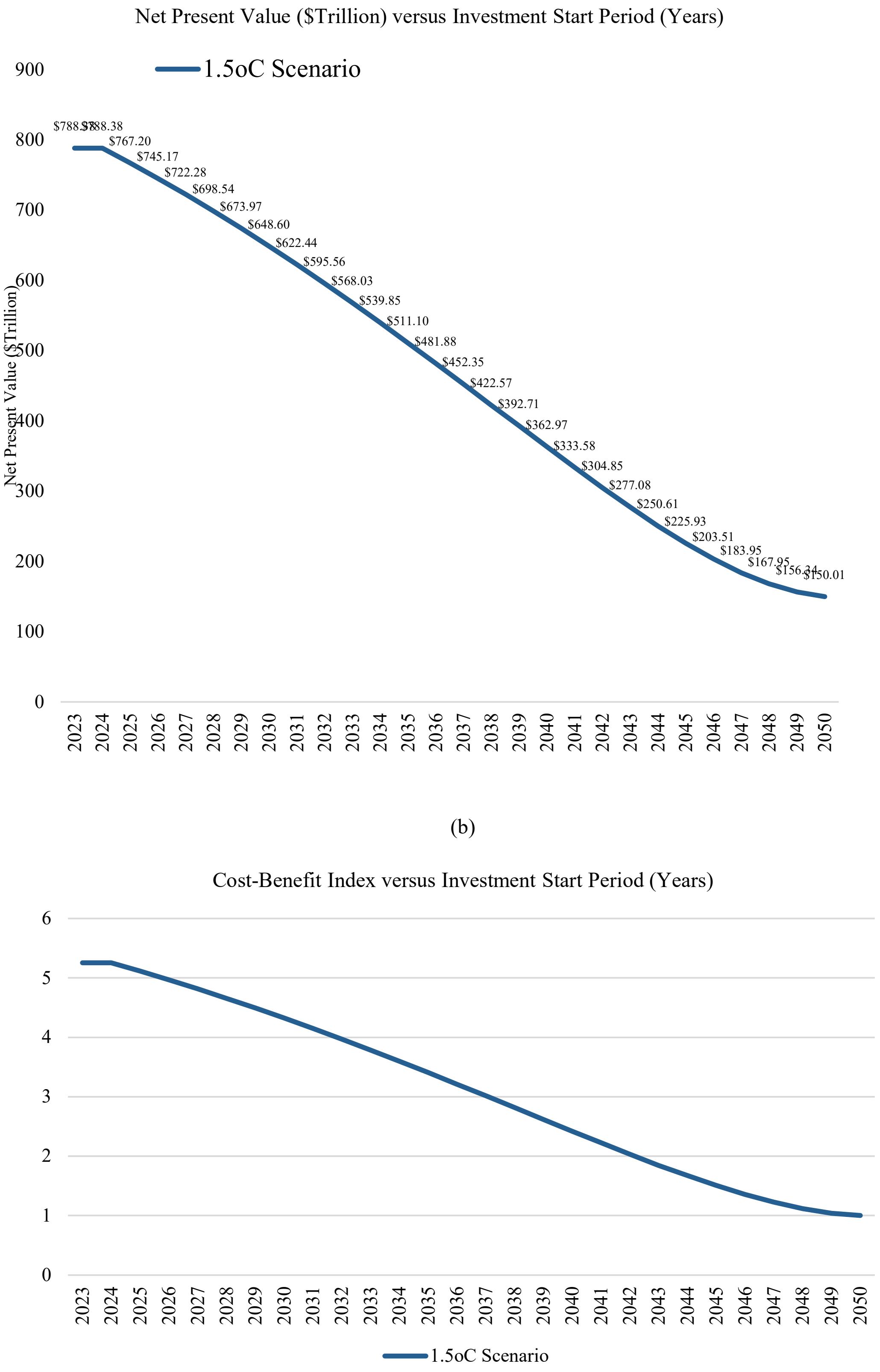
When contemplating the implementation of a policy scenario in the anticipated first year, it is crucial to acknowledge that the amount of investment required may vary if it is postponed to a different year.

This consideration should take into account potential risk variables that might have either negative implications, such as inflation, or positive implications, such as technological breakthroughs and cost reductions. Given the focus of our investigation on climate change risks, it is unlikely that a delayed investment would provide any favourable benefits.

Consequently, the net present value of an investment made in a subsequent year to attain an equivalent policy scenario is hypothesized to drop, hence equation (2.14). The best case (i.e., 1.5$^{o}$C Scenario) data shown in Figure 4.5 (a) – (c) is used to establish and fit the model that assumes a reverse correlation between the emissions cost discounting rate (R) and the net present value (NPV).



(a)



(b)

(c)

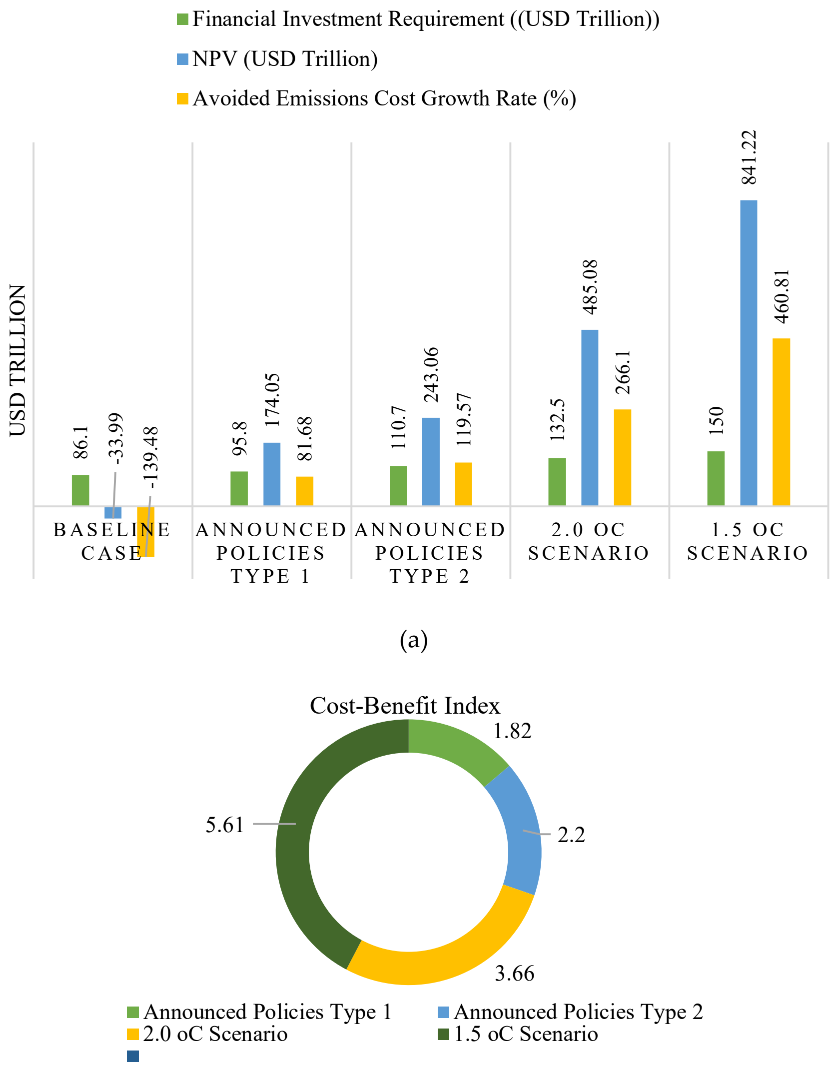
**Figure 4.5.** Plot of model fitting using the 1.5ºC scenario investment. (a). Real GDP from 2000 to 2050. (b). net present value ($trillion) versus investment starts period (years). (c). cost-benefit index versus investment starts period (years)

## 4.4 Results and Discussion - Global Policy Scenario

### *4.4.2 Findings for Simulated Global Policy Scenario*

In this part, Figures 4.6, 4.7, and 4.8 show the outcomes of the NPV, Avoided Emission Cost Growth, and Cost Benefit at different discount rates of the five policies for the year 2050.

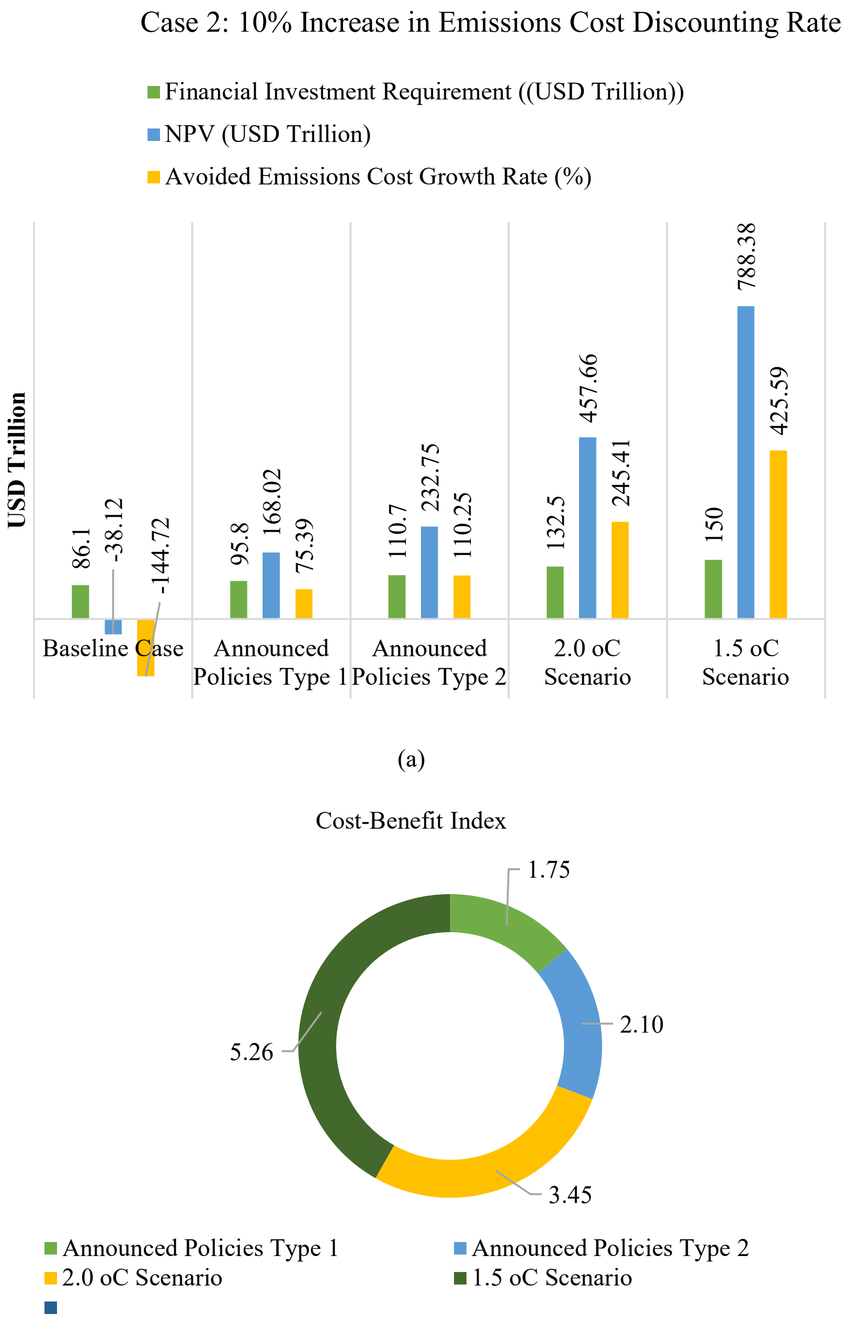
Case 1: Use of the initial Emissions Cost Discounting Rate used for the simulation of policies in chapter three.



(a)

(b)

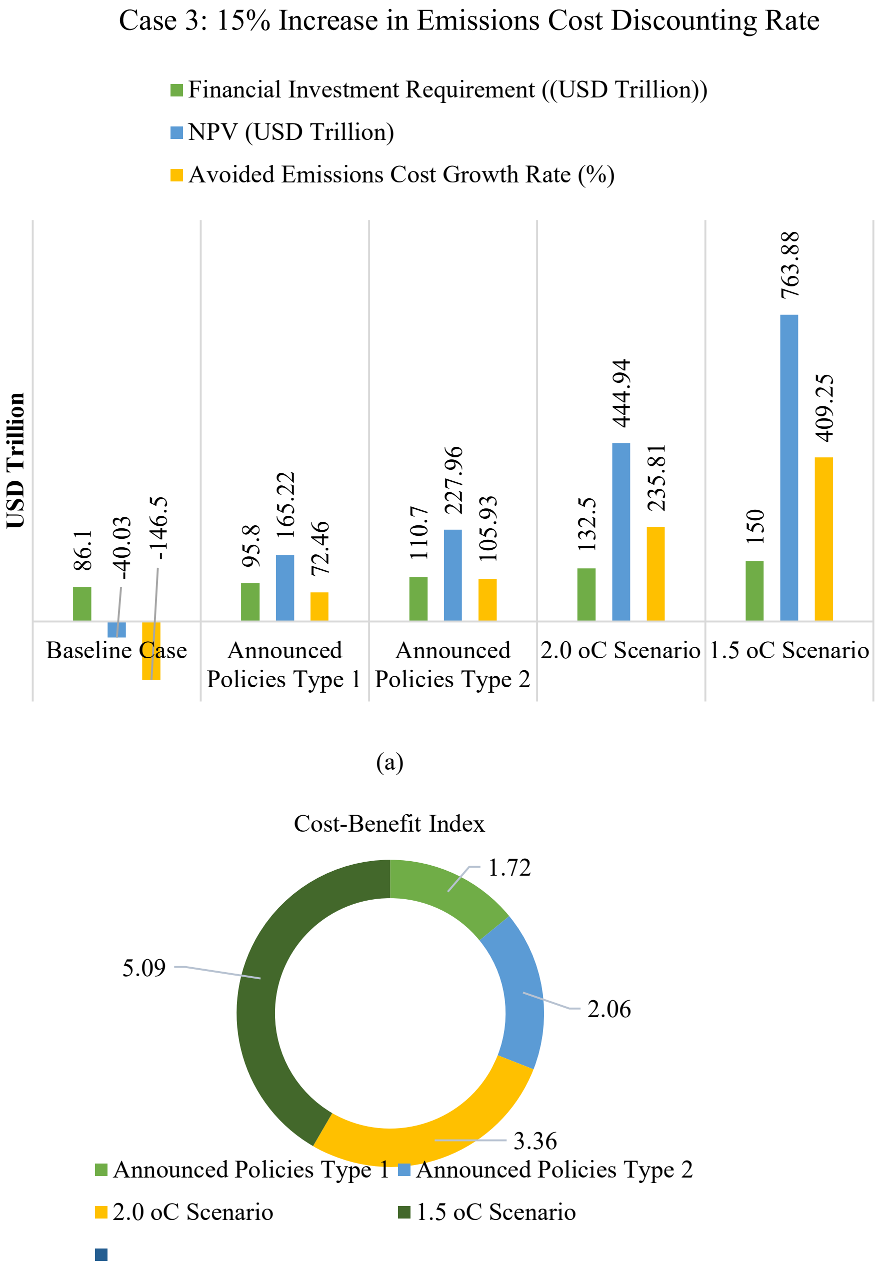
**Figure 4.6.** Case 1: (a) net present value and (b) cost-benefit index of global policy scenarios.



(a)

(b)

**Figure 4.7.** Case 2: (a) net present value and (b) cost-benefit index of global policy scenarios



(a)

(b)

**Figure 4.8.** Case 3: (a) net present value and (b) cost-benefit index of global policy scenarios

### *4.4.3 Summary*

a. Net Present Value of Policies of Cases 1, 2, and 3

Figures 4.6a, 4.7a, and 4.8b show the financial requirements, with the NPV and Avoided Emissions Cost Growth when the discount rate per policy is between (2.29 - 2.48)%, (2.52 – 2.73)%, and (2.64 – 2.85)% for cases 1, 2, and 3 respectively and with reference to table 5. In the baseline scenario of case 1, the NPV is -33.99 USD Trillion, showing that the value of emissions commitment in the first year of 2023 is not useful, and hence, such investment is not advisable. In the other four scenarios, the NPV are 174.05, 243.06, 485,08, 841,22 USD Trillions for announced policies type 1, announced policies type 2, 2.0 ºC scenario, and 1.5 ºC scenario, respectively. As with case 2, the base scenario has an NPV of -38.12 USD Trillion. Hence, this shows that the value of the emissions pledge in the first year of 2023 is not useful, too, so it is insufficient to reduce emissions. For stated policies type 1, and announced policies type 2, the NPV are 168.02, 232.75, 457.66, and 788.38 USD Trillions, respectively. Similarly, case 3 produces an NPV of -40.03 USD Trillion, with 165.22, 227,96,444.94, and 409.25 USD Trillion for the respective four scenarios. As can be found, the NPV reduces with an increase in the discount rate, as it is from case 1 to case 3, which is in line with the well-known fact that the NPV of investment diminishes with an increasing discount rate [280], [281]. Therefore, in line with the work by Wang Z. et al. [282], which presents that the unit cost of emissions removal would likely increase in the short term. Such can be attributed to inflation and increased cost of financial requirements per policy. Hence, increasing GDP does not guarantee an increase in NPV of a delayed investment towards achieving a particular emissions reduction policy.

Similarly, the avoided emissions growth rate among the five scenarios and three cases depreciate with increasing discount rates. These differences are compared in Figure 4.9. While the financial commitment in the announced policies type 1 and announced policies type 2 have been able to reduce the emissions growth rate and have a positive NPV, it is still insufficient to reach the 1.5 to 2.0 ºC scenarios. An earlier study by Akimoto K. et al. [283] analyzed the economic costs of achieving NDCs and expected global emission pathways of 1.5 and 2.0 ºC. It found that emission reduction costs vary widely among countries, leading to carbon leakage. Our study has provided further analysis of the NPV and BI of these pathways, as well as the time value of policy decisions used to validate our model, as discussed in section 4.7. The expected global emission reduction is smaller than predicted by aggregating reductions, and emissions are larger than those required for temperature stabilization, as suggested by the same studies [283].

The effectiveness, efficiency, uniformity and equality of Carbon allocation and emissions mitigation towards the desired global temperature scenarios continue to be a challenge, with the suggestion of preferences for utilitarianism-egalitarianism trade-off [284], national renewable expansion and sectoral reduction targets at the level of municipalities [285], equitable energy demand reduction [286], and assessment of remaining Carbon budgets size and uncertainty. The work by Fyson C. [287] suggests fair-share outcomes for the top emitting countries, the USA, EU, and China, which could result in 2-3 times larger $CO_2$ mitigation responsibilities this century and possible costs, as found in this study. The debate on equitable mitigation contributions is crucial for progress and in the assessment of more equitable economic costs by employing the model developed in this study. As part of an attempt to address this challenge, Hales R. and Mackey B. in [288] presented a perspective of equity in the carbon budget, the scale of achieving the Paris Agreement global temperature goals. In a follow-up, Akpan J. et al. [289] employed a fair sharing approach in simulating the emissions budgets of the same USA, EU, China, and, in addition, India's transition into the 1.5, 2.0 °C, and alternative scenarios. The emissions budgets, which are in line with the philosophy of Zimm C. et al.'s [290] recent work on justice consideration for climate change mitigation research are then used in assessing the economic attractiveness and benefits as presented in section 4.5.

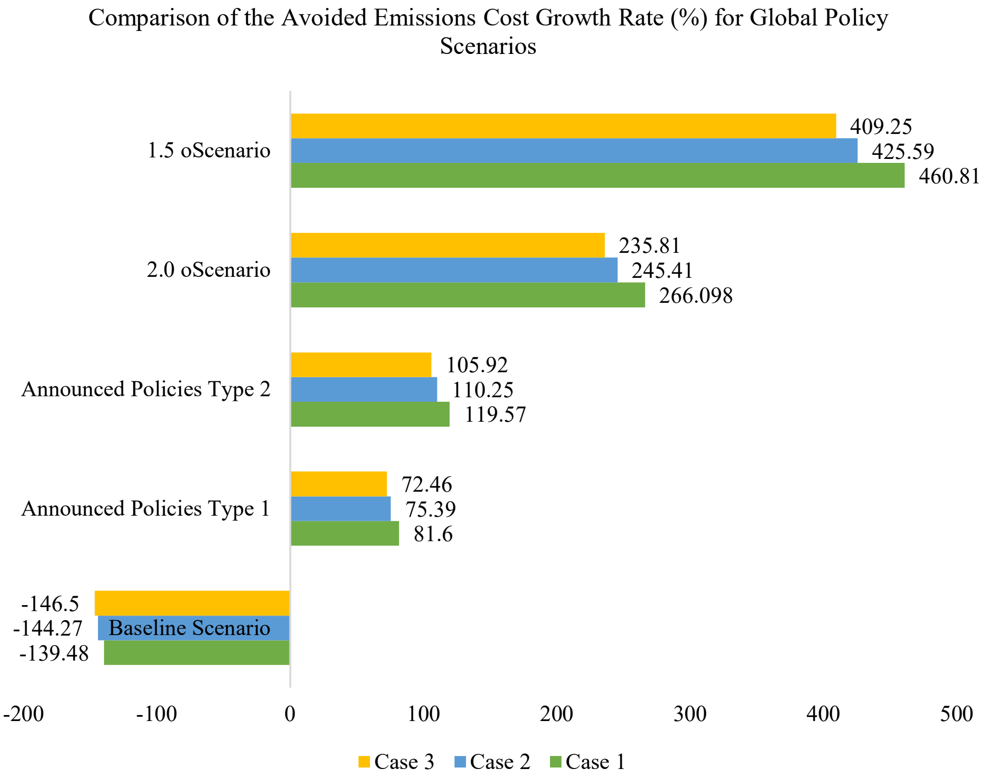


**Figure. 4.9.** Comparison of the avoided emissions rate for the global policy scenarios

In terms of comparing the avoided emissions growth rate among the five scenarios and three cases, Figure 4.9 shows that the rate of reduction from the investment of the 1.5 °C scenario results in the highest reduction of emissions compared with the other four scenarios. Whereas, in the baseline scenario, emissions are rather not avoided, resulting in a growth rate between 139.48% to 146.5%. It implies that the financial commitment is insufficient given the 2.4 USD Trillion unit emissions removal cost. Also, even though signs of progress are made in mitigating emissions, the accumulated amount of $CO_2$ eq already present in the atmosphere would still need to be removed. Hence, the a need for additional financial requirements in the other scenarios.

b. Cost Benefit of Policies

While the financial commitment in the announced policies type 1 and announced policies type 2 have been able to reduce the emissions growth rate and have a positive net present value, it is still insufficient to reach the 1.5 to 2.0 ºC scenarios. Comparing the differences in the benefits from each scenario as shown in Figures 4.6b, 4.7b, and 4.8b. and 8, 1.5 ºC scenarios have a very high benefit of 5.09 in relation to 3.36, 2.06, 1.72 of the 2.0 ºC, announced policies type 2, announced policies type 1 scenarios. The baseline scenario has a negative benefit, and as a result, such an investment venture should be highly rejected, in accordance with Table 4.2.

## 4.5 Illustrative Application of Emissions Budgeting Model to Other Cases

### *4.5.2 Overview*

Achieving a transition to net-zero emissions requires investing an unprecedented number of financial commitments in clean energy sources [230]. China, the USA, India, EU are the major emitters of $CO_2$, and reducing current Carbon in the atmosphere as well as committing to the reduction in further emissions from these countries and regions could highly facilitate the transition of the world into a net-zero society. In the report by IEA in [230], three forward-looking scenarios (net-zero, SDG, and stated policies) were defined and used to provide a landscape for clean energy financing in emerging and developing economies. The net-zero, SDG and stated policies scenarios were compatible with approximately 1.5, 2.65, and 3.0 ºC climate scenarios defined in this study. Consequently, the global energy investment report was developed in the current year of study by another IEA report [2]. In line with other separate energy and climate investment reports, Table 4.5 presents a summary of the financial requirements in both the planned (herein, 2.65 ºC) and net-zero scenarios (herein, 1.5 ºC) for China, USA, India, Europe, and the rest of the world. These values are, therefore, going to serve as the input data to estimate the indices for the emissions budgeting model developed in this study.

**Table 4.5.** Planned and net-zero financial/investment requirements for each country/region

| Countries/Regions | Finance Requirement (USD Trillion) (Planned Scenario) | Finance Requirement (USD Trillion) (Net-Zero) | Reported ideal duration of financial commitment | Reference for Finance Requirement Data |
|---|---|---|---|---|
| China | 15.3 | 22 | 2021 - 2050 | [239] |
| USA | 3.92 | 18.2 | 2022 - 2050 | [241] |
| India | 7.2 | 12.1 | 2022 - 2050 | [242], [291] |
| Europe | 5.4 | 28 | 2020 - 2050 | [240] |
| Rest of the World | - | 69.7 | 2020 - 2050 | Subtracted from the summation of China, USA, India, and Europe, and compared with the global financial requirement in world energy investment report by IEA in [101] |
| World Total | 103 | 150 | 2023 - 2050 | [101] |

The information and data in Table 4.4 were gathered from several sources already referenced and standardised to a single operational measure of financial requirements.

### 4.5.3 Assumptions

The direct and indirect costs of each policy have already been defined and accounted for within the cost presented in the appendix, Table A3 and A4. The avoided and unavoided emissions costs are obtained to allow for the Estimation of the budgeting indices. Two assumptions are introduced as described in Table 4.6 below.

**Table 4.6.** Assumptions for estimation of avoided and unavoided emissions costs for the illustrative case studies

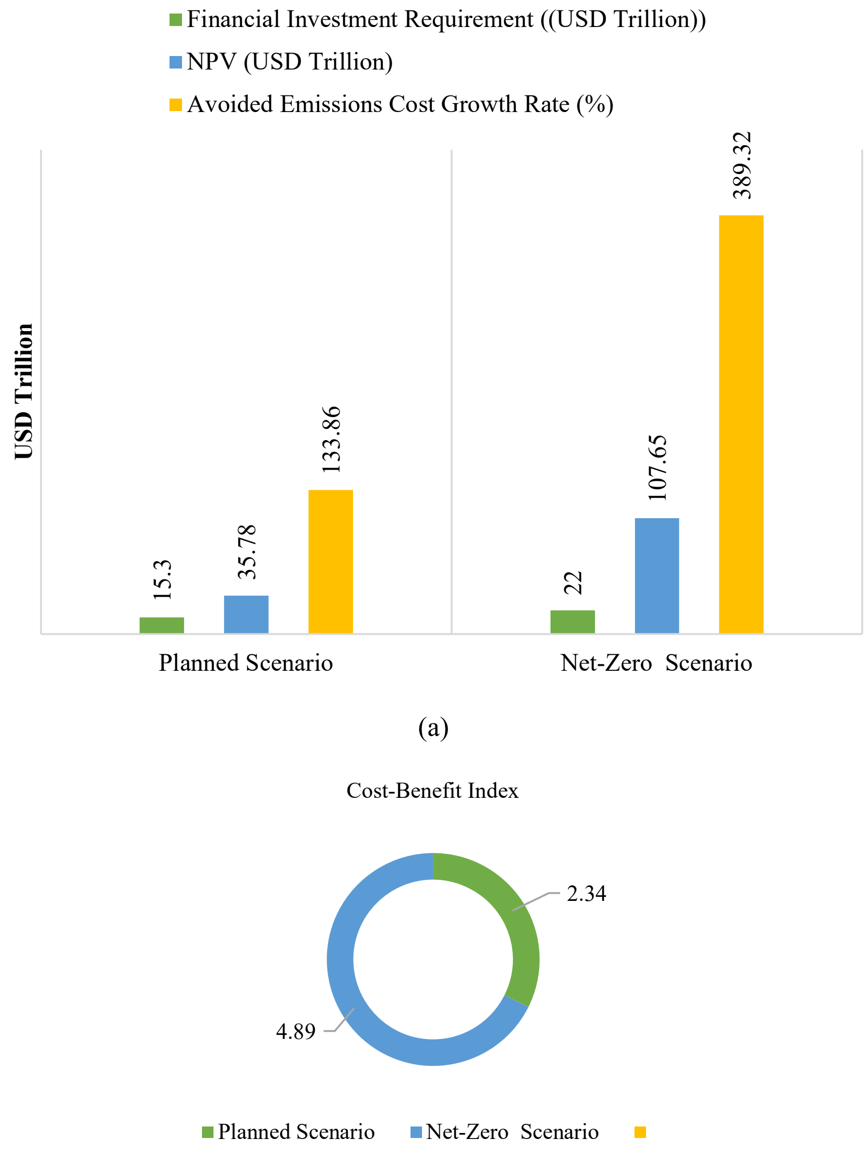
| **No.** | **Assumptions** | **Description** | **References** |
|---|---|---|---|
| 1 | Use of Global Values | The unit cost of removing emissions value of 1 Gtons $CO_2$.eq, which represents 2.42 USD Trillion, is used. | Calculation as per eq (2.3) – (2.5) |
| 2 | Use of National Values | The GDP growth rate was used as an emissions cost discounting rate and calculated at the country/regional level. | Calculation as per eq (2.11) with data from OECD in [220] |

Therefore, based on equations (2.3) – (2.5), the unit base cost of emissions removal, avoided, and unavoided emissions costs are estimated. Also, the emissions cost discounting rate average GDP growth rate was calculated based on equation (2.11), with the input data from the individual year GDP projection data obtained from OECD [220]. The GDP projection, which includes long-term baseline forecasts until 2060, is produced from an analysis of national and international economic conditions. This assessment is carried out by combining model-based analysis with experts' opinions. This metric is often calculated in US dollars (USD) using 2010 constant prices and Purchasing Power Parities (PPPs).

### 4.6 Results - Other Case Studies

With the use of Figures 4.10 – 4.13, this section presents the NPV, avoided emission cost growth, and cost-benefit findings for China, USA, India, and the EU for the year 2050 at discount rates according to Table 4.6.

a. China

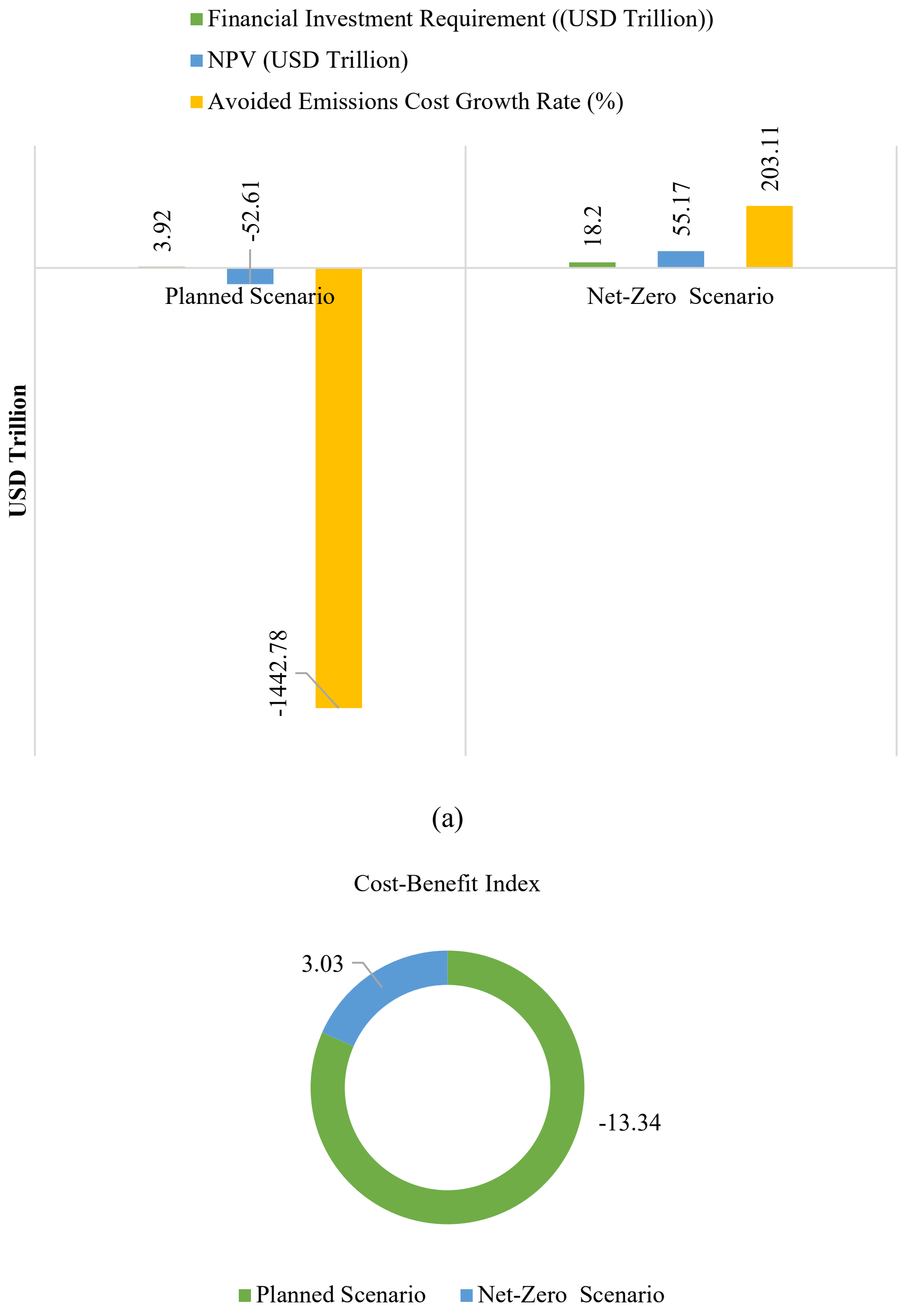


(a)

(b)

**Figure 4.10.** China: (a) net present value and (b) cost-benefit index

### b. The USA

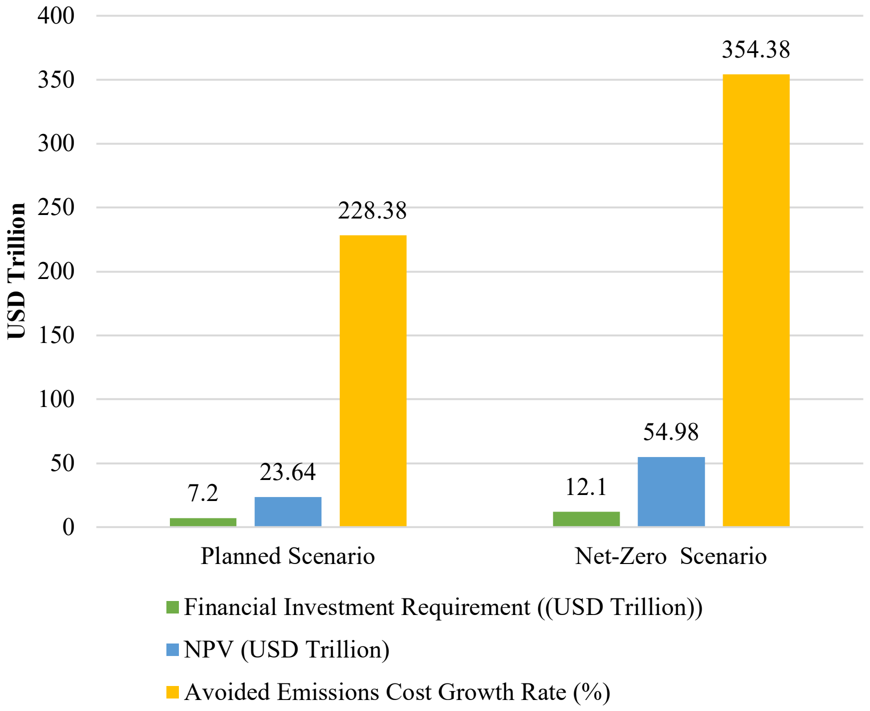


(a)

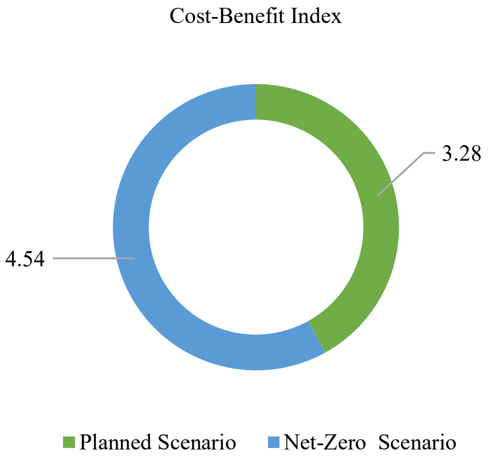
(b)

**Figure 4.11.** The USA: (a) net present value and (b) cost-benefit index

c. India



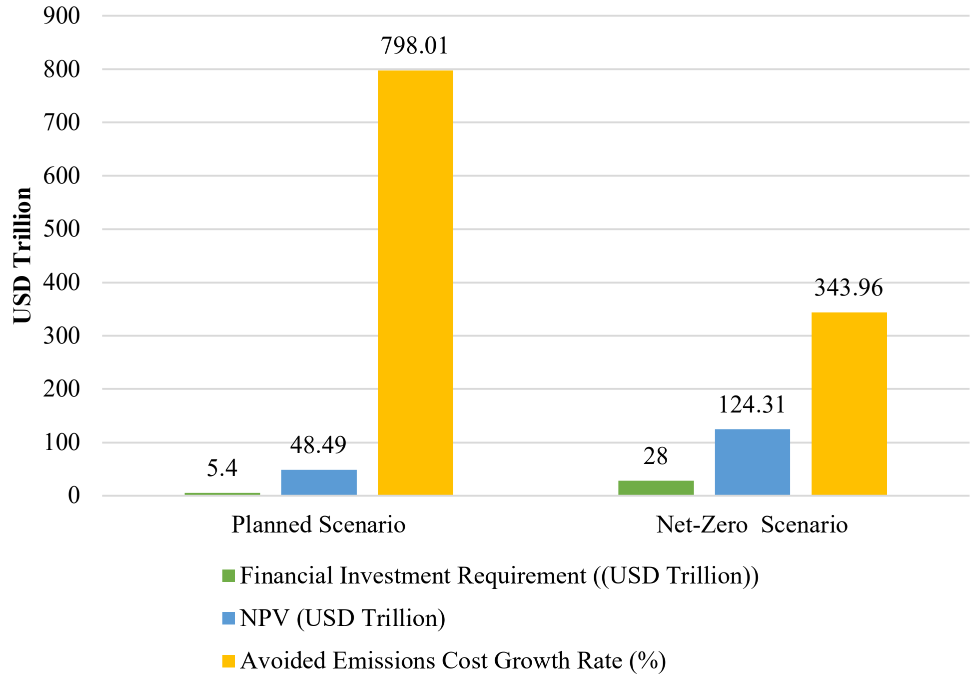
(a)



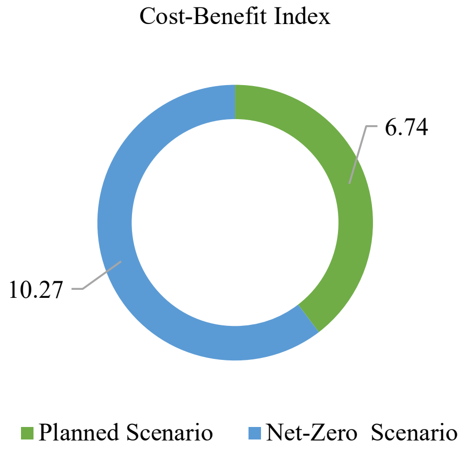
(b)

**Figure 4.12.** India: (a) net present value and (b) cost-benefit index

d. The EU



(a)



(b)

**Figure 4.13.** The EU: (a) net present value and (b) cost-benefit index

Figures 4.10 (a), 4.11 (a), 4.12 (a), and 4.13 (a) show the financial requirements, with the NPV and avoided emissions cost growth for China, USA, India, and the EU. Similarly, Figures 4.10 (b), 4.11 (b), 4.12 (b), and 4.13 (b) show the cost-benefit index for the same countries, respectively.

### *4.6.2 Summary of the Illustrative Application of Emissions Budgeting Model to Other Cases*

In the planned scenario, except for the USA with -52.61 USD Trillion, the NPV of the financial commitment for emissions reduction are all positive for China, India, and the EU with corresponding values of 35.78, 23.64, and 48.49 USD Trillion, respectively. Therefore, the current commitment in the USA has to be increased as continuously following the baseline scenario is highly insufficient to reduce the emissions value needed towards the ne-Zero scenario.

Following the net-zero scenario, all countries showed a positive NPV, with China, the USA, India, and the EU having 107.65, 55.17, 54.98 and 124.31 USD Trillion, respectively. Meanwhile, the commitment across each of the other four countries yielded NPVs that are not directly proportional compared with all the countries in both the planned and net-zero scenarios. These differences can be explained in Figure 4.14 with the avoided emissions growth rate across the four countries and two scenarios in each.

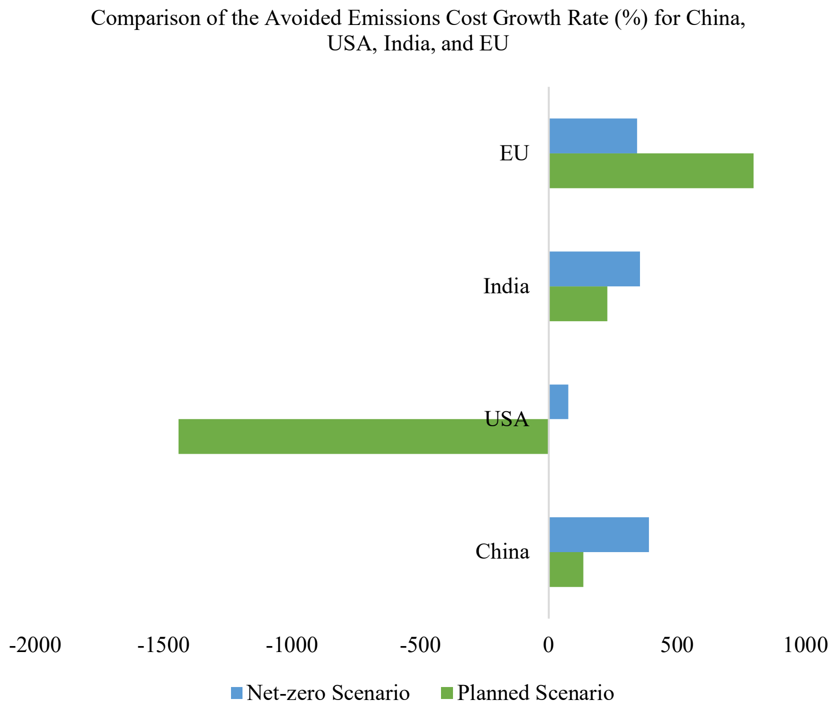


**Figure 4.14.** Comparison of the avoided emissions rate for China, USA, India, and the EU.

a. Net Present Value of Policies in China, USA, India, and the EU

In terms of comparing the avoided emissions growth rate among the planned and net-zero scenarios in the four countries, figure 4.14 shows that the rate of reduction from the net-zero investment results in the highest reduction of emissions compared with the planned scenarios. The planned scenario showed that the USA would likely have an increase in unavoided emissions rate of -1442.18%. The implication is that the financial commitment is insufficient given the 2.4 USD Trillion global unit emissions removal cost. Furthermore, though the NPV in the EU is higher in the net-zero scenario than the planned scenario, the avoided emissions cost growth rate in the planned scenario is rather higher than in the net-zero scenario. Owing that the financial requirements estimated for the actual planned scenarios and the reported financial requirements for the net-zero scenarios in the EU may have used different unit costs for removing a unit ton of $CO_2$. Hence, resulting in the differences as in this study, as a single value was used across the four countries to avoid the differences that have been acknowledged in literature [292], [293], that the cost of removing (i.e., both using low and net-zero technologies, Carbon capturing and sequestration of a unit ton of $CO_2$) varies across industries and countries.

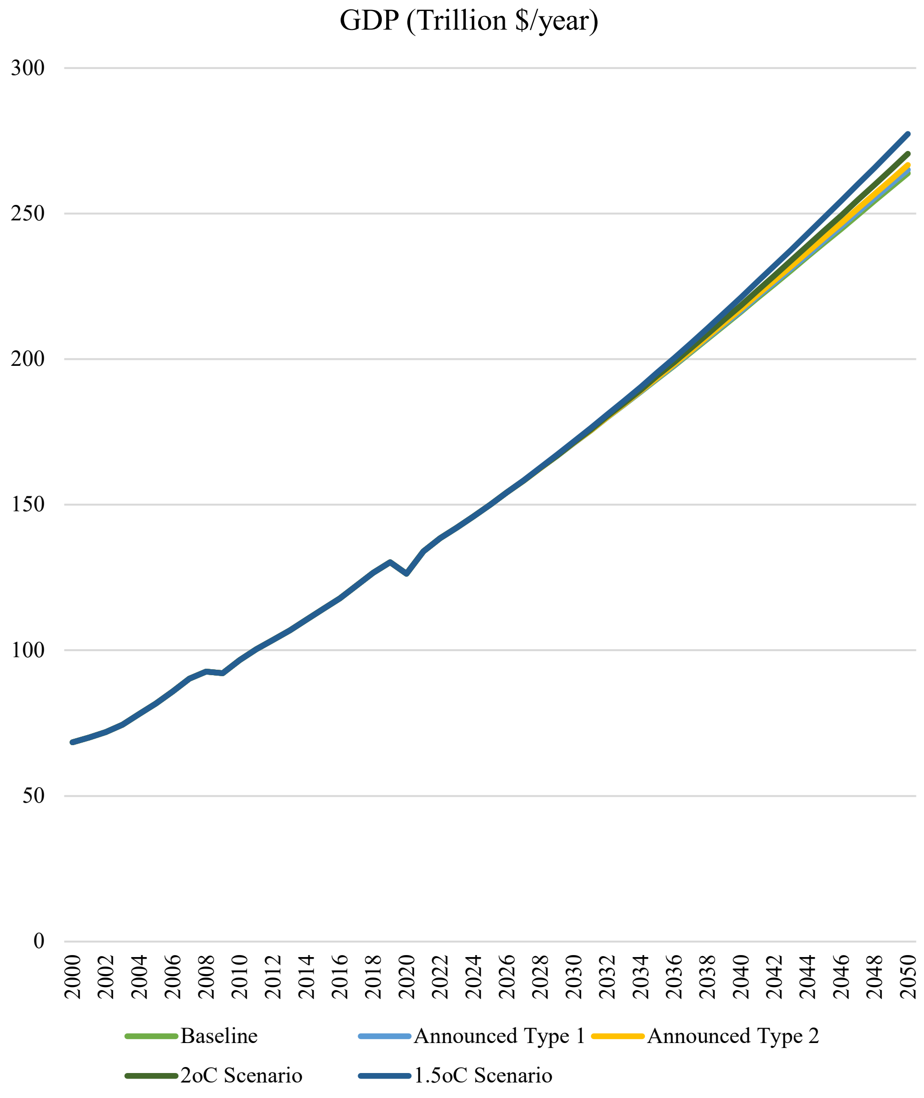
b. Cost Benefit of Policies in China, USA, India, and the EU

While the financial commitment in the planned scenario of the case study countries has been able to reduce the emissions growth rate and have positive net present value except for the USA, the net-zero scenario continues to be the best pathway to follow towards reaching the 1.5 to 2.0 ºC scenarios since these four countries have continuously been the major global emitters. Comparing the differences in the benefits from each scenario, as shown in Figures 4.10 (b), 4.11 (b), 4.12 (b), and 4.13 (b), the net-zero scenarios for China, India, and the EU have the best benefits of 4.89, 4.54, 10.27 in relation to 2.34, 3.28, 6.74, respectively, except for the USA with no benefit (i.e., BI value is -13.42) in the planned scenario, and 3.03 in the net-zero scenario.

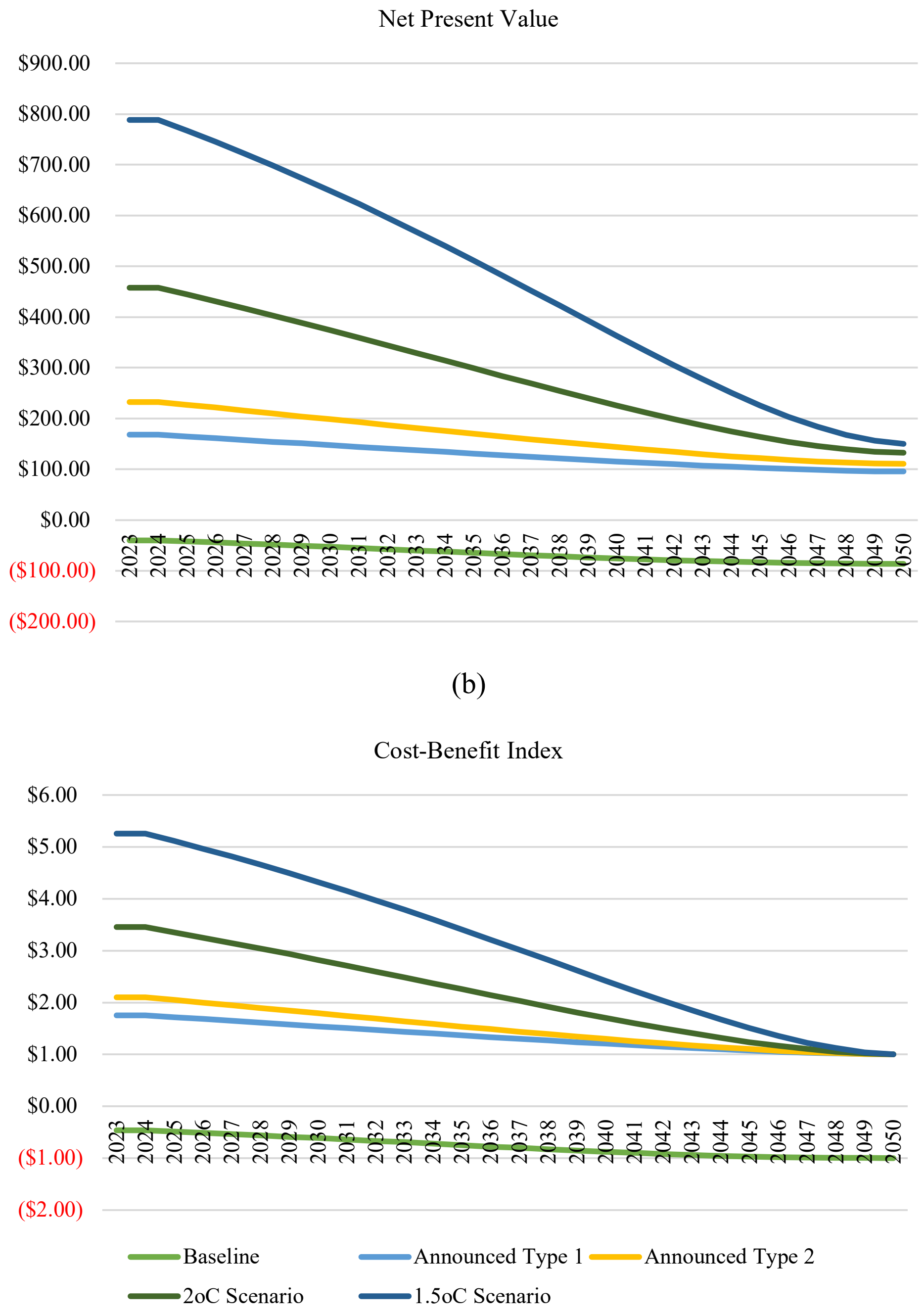
## 4.7 Model Validation and Limitation

In order to validate the model, the time value of each policy scenario using the principle of capital budgeting through the net present value and cost-benefit of each policy is carried out in this section. The fitness model in equation (2.13) shows that delayed policies result in a net present value and cost-benefit that may be different from using the same initial financial requirement to start implementing from the first year as planned. Hence, in the model validation, using the same initial financial requirement, the start of the policy implementation is delayed to the succeeding year, and that is done continually until the last year. For instance, in the 1.5 ºC scenario, the investment that was meant to start in 2023 was started in 2024 using the same initial financial requirement.

Also, the envisaged GDP of each policy option used in estimating the emissions values, as in Chapter 3 of this thesis, was used in estimating the emissions cost discounting rate based on equations (2.10), (2.11), and (2.12) of this Chapter, as shown in Figure 4.15 (a). After that, the emissions cost discounting rate was employed to calculate the NPV of each policy at delayed investment. The model showed that the NPV and BI values on each policy option depreciated as compared to starting the investment in the first planned year. The results in Figure 4.15 (b) and 4.15 (c) showed that with increasing delay in policy implementation, the NPV and BI of the initial financial requirement continue to diminish in the succeeding years at an increasing GDP. The outcome of this validation is in line with real-world cases where an increasing GDP often leads to inflation and an increasing cost of capital to execute projects that should have been made earlier on at the least cost.



(a)



(c)

**Figure 4.15.** Model validation with the global scenarios

Since the dangers associated with climate action are expected to rise over time, the time value of policy scenarios from the previous section shows that delaying action to reduce greenhouse gas emissions would be counterproductive and less economically attractive. The transition to keep the earth within the 1.5 ºC climate scenario has been explored and is deemed to be doable by a number of publications and papers, such as the ones in [175], [294], [295], [296], [297], [298], that look at the technical feasibility of accomplishing the climate objectives and achieving sustainable development**.** However, the challenge has often been seen as mainly financially demanding [148], [231], [238]. In the evaluation of the financial requirements of the policy scenarios through this study and in the findings from sections 4.5 and 4.6, the economic benefits of the 1.5 ºC climate scenario cannot be overemphasised.

Considering this, it's clear that cutting emissions today is far wiser than waiting, and more financial regulatory mechanisms are needed because of the possibility of catastrophic losses due to climate change [235]. If all countries and regions stop emitting $CO_2$ this year, the environment could benefit next year and every year after that. Whereas if some regions start cutting emissions in 2030, the global carbon budget would have been drained for another extended period, making it unlikely that we can meet the 1.5 ºC scenario. In terms of environmental cost advantage, the payback time for following the 1.5 ºC scenario can be seen immediately and before 2050, as the climate change consequences of further damages are averted through the reduction of emissions concentration in the atmosphere. Since $CO_2$ has had a warming effect on the planet over decades, it's important to think about carbon stocks and fluxes in the atmosphere when planning for emissions mitigation.

Despite the study's useful insights regarding the economic importance and attractiveness of emission reduction policies, it is important to acknowledge the limitations and weaknesses in the study's design and execution when interpreting the results.

The model developed in this chapter may not be a full representative of the peculiar challenges at large because it focuses on just four countries—China, the United States, India, and the European Union, and the global level without the unique challenges of other individual countries. Therefore, the results may not absolutely apply to other countries or regions. Additionally, the study assumes that emissions mitigation policies would be implemented according to the planned timeline, which might not match up with the real situation. The study disregards the potential challenges and constraints to policy implementation, which may affect the economic attractiveness of such policies.

Also, the study does not take into consideration how emission reduction policies could affect society and the environment. The study does not include a detailed and thorough understanding of the policies' overall consequences since it solely considers the economic benefits and risks. Consequently, some complexities in emissions mitigation policies were not adequately incorporated by the study's simplified emissions cost budgeting model. Hence, the accuracy of the results and the conclusions derived from them may be influenced by the assumptions and limitations of the model.

Both regions or countries' non-uniformity in the reduction goals and continuing to follow the current paradigm of climate goals without swift action is detrimental because the required path to the 1.5 ºC scenario is already over-ambitious; hence, a rare case to find regions exceed the simulated 1.5 ºC Scenario reduction goal to create a balance for the deficiencies of other countries.

As with the case of climate actions, environmental needs are very important, as failure to mitigate the consequences can be more catastrophic. The consequences of inaction might be disastrous; therefore, now appears the best time to act. Since $CO_2$ has had a warming effect on the planet over decades, it's important to think about carbon stocks and fluxes in the atmosphere; hence, shifting into swift action of high financial investment with cost benefit.

The energy requirement and current cost for emissions capture are high and vary across countries due to differences in storage location, high design complexities, and customisation needs. Albeit, the future unavoided emissions cost could be decreased if initiatives and emissions capture technologies cost are also reduced. However, such breakthroughs are yet to happen; hence, the timeliness of deciding on the present is pertinent.

## 4.8 Conclusion and Policy Implication

The EB model from this Chapter helps analyse the investment attractiveness across the different policy scenarios. The results from the policy scenarios show that a little difference in financial investment options aimed at mitigating emissions could lead to a greater cost benefit. For instance, in terms of:

*Economic Benefits:*

- In the global scenario simulation and at the first case of no emissions discount growth, the 1.5ºC scenario achieved a higher NPV of $USD 841.22 Trillion and BI of 5.6, with an initial investment requirement of $USD 150 Trillion, compared with the 2.0ºC scenario having the NPV of $USD 458.08 and BI of 3.66, yet with the initial financial requirement of $USD 132 Trillion. The baseline scenario resulted in negative NPV and BI. Hence showing the consequences of the world continuing in the business-as-usual approach to emissions reduction. Meanwhile, the Announced Policy Type 1 and 2 yielded positive NPV, implying that such investments could create economic and social benefits. However, it is not adequate to keep the world within the recommended temperature levels.

- In the illustrative case studies, according to the model's estimation and results in section 4.4 and the illustrative application of the model to China, the USA, India, and the EU in section 4.5, investment options towards the global temperature rise show that apart from the environmental advantages of the 1.5 °C and net-zero scenario, a huge present economic value is also very high compared with the rest of other scenarios. In all the planned scenarios for China, India, and the EU, emissions reductions made are insufficient to meet the net-zero scenario target. For the USA, the current commitments are not only insufficient but capable of resulting in increasing emissions cost, as the avoided emissions growth rate would be continually reduced. This finding provides valuable information for stakeholders and policymakers to see the investment option towards the 1.5 °C scenario as beneficial and capable of producing sustainable economic and social development.

*Emissions Mitigation Benefits:*

- In the global, the findings showed the emissions cost growth rate became reduced alongiside the NPV, BI,  in the policy with higher increasing GDP. The change can be attributed to the real-world situation of increasing capital costs for a delayed investment due to increasing high financial risks. A study by Gryglewicz S & Hartman-Glaser B. [299] supports this assertion that delaying investment for large projects is with cost. Hence, using the model of this Chapter, growth opportunities towards emissions reduction, such as the ones that largely affect global temperature levels can be accessed using different risk factors such as inflation, incentive cost, and taxes/subsidy changes.

Therefore, it can be deduced in this case that early policy decisions for emissions reduction are more valuable than decisions made later. The additional financial commitment made today has a higher economic value and can significantly reduce unavoided emissions costs in the future. The study by Wang Z. et al. [282] affirms this claim made in this study about early policy actions presented as being instrumental in abating future emissions cost: as MAC under the constraint of carbon emission reduction targets were analysed for different regions in China by the same Wang Z. et al. [282], and findings showed that emissions cost could hardly be reduced in the short term, but rather may be possible in the long terms. In this case, the long-term benefits of emission cost reduction would have no climate benefits. Therefore, governance frameworks and policies towards emissions should prioritise the timeliness of implementation rather than seeing initial cost as the main reason for delayed decisions.

The model in this study classified several countries as one region except for China, the USA, India, and the EU. For instance, the rest of the advanced countries and the rest of the developing countries are regarded as separate regions. Apart from the EU, China, India, and the USA, it is undefined how individual developing countries and advanced countries could play a part in the emissions reduction measures. Hence, apart from the regional approach used in this study to emissions reduction planning, further research could use the same model developed in this study to investigate the budgeting indices for each country while strategising an average emissions reduction within the ranges this study has used. Such studies could help all countries to move towards a sustainable and net-zero society progressively. For instance, a fair rationing index for emissions reduction at each selected country under the rest of the developing and advanced countries categories can be introduced using such policy scenarios from this study to simulate the best reduction ratios with envisaged yearly emissions flow and the best investment values that concentrate on key energy and climate development indicators towards the emissions reduction. It is important to explore how energy and climate policies can help to manage the envisaged increase in emissions without placing many constraints on energy development for accessibility, affordability, and security while committing to the success of the NDCs. The result from such index values could help promote the inclusiveness of each country's economic size and infrastructural needs and a just transition that allows support, with bias, the goals of sustainable development. More importantly, this development should be more supportive of clean energy technologies to contribute to the nationally determined contribution of mitigating emissions.

In this chapter, the developed simplified framework for emissions mitigation planning and budgeting, using all sectoral contributions as a single value obtained from the simulated values in chapter 3, aligns science, policy, and practice and could guide nations, organisations, and communities in curbing emissions and securing a sustainable, resilient, and equitable future through understanding the time value of whatever policy decision is made. For instance, V. Vecchi et al. in [300] discussed how NPV can be used to secure a better business investment deal. This study believes that the use of NPV in energy and climate transition narratives can serve as a convincing and attractive tool to get the full commitment of individuals, companies, and public and private sectors to commit to increasing the financial requirement needed towards the 1.5 $^{o}$C. Hence, the business of climate change should not be seen as expensive but the value creation in terms of economic benefits capable of creating green jobs, avoiding future emissions occurring, and the associated costs resulting from high inflation and discount rates.

This research contributes to the growing body of knowledge towards achieving the ambitious goals of the Paris Agreement. In order to enhance the simplified model introduced in this thesis, capital budgeting indices like ARR, IRR, and PBT can be introduced, as the present model only computes NPV and BI indices. Therefore, future work can also consider these indices alongside the heterogeneity challenge in a unit cost of removal of emissions estimation, as this study assumed a single value for all the policy scenarios, as explained with justification in section 4.3.4 of this Chapter.

From the model developed in this chapter, the use of the simplified emissions budgeting model can be applied in three key recommended areas below:

- *Integration into Existing Climate Models:* The models employed in this study may be linked or integrated to other established climate models that address the environmental impact of different policy scenarios for integrated evaluation that should also involve the economic attractiveness of each policy option. For instance, the C-ROAD model and several other integrated climate assessment models hardly or do not explain the economic benefits of different emissions mitigation policies.

- *Application Scalability in Other Countries, Cities, and Households:* the narrative in this study using a unit cost of avoided and unavoided emissions for the world, China, USA, Europe, and India have shown that delayed emissions mitigation may likely be more expensive if actions are delayed. Therefore, this same model approach can be applied to other cities, countries, industrial facilities, and even households to show the present value of different decisions and the likely future costs of emissions.

- *Insight for Establishing the Linearity of the Interconnectedness of Emissions Mitigation Pathways with Climate Scenarios:* The exact or approximate value of the contribution of complete emissions-free energy and industrial processes needed for the 1.5°C scenario continues to pose challenges in the investment attractiveness of policy decisions. Hence, further studies can concentrate on establishing this direct relationship of sectoral contributions, technology advancements, and transitions for a sustainable low-carbon future and reaching the 1.5 °C climate scenario.

Finally, climate scenarios, emissions budgeting, and planning should align with targets for the development and utilization of renewable energy, which have been strongly acknowledged to advance climate ambitions greatly. Hence, the next chapter of this thesis focuses on the discussions surrounding the transition into complete renewables in line with climate scenarios.

# Chapter 5

## Towards the 1.5 $^{o}$C Climate Scenario: Perspective Energy Model & Framework

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Submitted as: **Akpan J.**, Olanrewaju O. "A perspective analysis on the transition to 100% renewable energy versus the global temperature scenarios using EN-ROADS Model."

### 5.1 Introduction

#### *5.1.1 Background*

In achieving sustainable energy development goals (SED), the rapid adoption of RE is imperative, having recently gained traction and having an increasingly significant impact on the global energy sector. Governments develop energy policies to regulate and direct energy production, transportation, and consumption inside their borders. By promoting sustainable and affordable energy sources, these regulations are intended to increase energy security and guarantee a consistent electricity supply. Energy resources, environmental issues, political objectives to promote high RE investments and economic realities can significantly impact a nation's or region's energy strategy. The percentage of global electricity generated from renewable sources was projected to increase to 28% in 2022, from a 19% increase from 1990, which largely contributed to increased investment by at least a factor of three during the decade between 2000 and 2009 [57] [100]. Continuous recurrent updates over time of energy policy need to account for societal and technological developments and the appearance of new threats and possibilities to meet regulatory practices and drive for achieving 100% clean and affordable energy at urban, national, regional, and global levels. Increases in energy efficiency and new energy policies have led to a rapid expansion of the renewable energy (RE) business, and because of the urgent need to address the issue of global warming and the sustainable development target [301], as most countries are expected to switch to renewable energy exclusively between 2030 and 2050 [89], [90], with countries expected to contribute to climate change fight by supporting in the RE target through high involvement in energy transition to full renewables. A recent literature study by N. Heidari and J. M. Pearce in [302] concluded that a high value for liability mitigation would provide considerable incentives for the adoption of renewable energy technology when greenhouse gas (GHG) emitters began to be held liable for damages resulting from GHG emissions that caused climate change and to commit to financial obligations that could be set on them. Notably, the investments in renewable energy capacity worldwide (excluding large-scale hydropower) reached USD 2.7 trillion between 2010 and 2019, with the largest contributions coming from China (USD 818 billion), the United States (USD 392.3 billion), Japan (USD 210.9 billion), Germany (USD 183.4 billion), and the United Kingdom (USD 126.5 billion), but in juxtaposition to the expenditure of USD 143 billion allocated towards the construction of new nuclear, coal, gas, and fuel-oil power plants during the year 2016, an approximate sum of USD 297 billion was dedicated to the financing of renewable energy sources [57].

With the increasing commitment to replacing fossil fuels with renewable sources, there is a potential to replace conventional energy systems fully. Effective energy distribution across regions requires robust energy storage systems, flexible demand–response mechanisms, and resilience infrastructure. The transition necessitates significant upfront investments and can potentially disrupt industries and provide notable social, environmental, and economic benefits.

### *5.1.2 Structure of the Chapter*

This chapter discusses the methods and evaluation approaches needed to reach 100% renewable energy (RE) systems. This study aims to create comprehensive literature on methods, metrics, and indices for research on 100% renewable energy (RE) systems that would be particularly valuable for researchers seeking to explore specific aspects of the literature and analysis methods in this emerging field. Currently, the literature on 100% RE systems is widely scattered and lacks a thorough collection of methods and evaluation approaches. This chapter aims to provide insights into the 100% renewable energy systems research field and the possibility of achieving such an endeavour through a simulation-based approach, laying a foundation for the discussion to synthesize different approaches towards a common methodology and modelling tool for 100% RE analysis. It covers a comprehensive range of articles to gain further direction and develop open-ended questions into various aspects of the research field, enhancing the overall understanding of the best methods useful in this subject matter.

The chapter discusses six methodological or evaluation mechanisms (herein, identified as 100% RE performance metrics) suitable for 100% renewable energy analysis based on an earlier explanation of the concept of 100% RE. It is followed by a review of existing energy modelling tools (EMT) under two criteria. The first criteria were to combine the existing modelling tools and place them under seven categories of the tool's usage at local or individual, island, national, global, all-purpose, 100% RE studies, and transition analysis. The second criterion selects the tools identified in the first criteria to be useful in 100% RE analysis, then benchmarks them with their capability to carry out the 100% RE evaluation metrics proposed in this study.

### *5.1.3 Contribution of the Chapter*

The contribution of this chapter is the presentation of the comprehensive approaches and evaluation procedures needed to realize the objective of developing energy systems that rely only on renewable sources, often known as 100% renewable energy (RE) systems. With this state-of-the-art literature having prospects for applicability, more sustainable and equitable energy systems needed to meet the climate scenarios target can be developed. The current corpus of research on 100% RE systems is characterized by its scattered nature and a lack of comprehensive methodology and assessment frameworks. This chapter bridges contributes to bridging this gap by providing unique insights into the research field of fully renewable energy systems. This discussion contains several works that can serve as additional insights and inspire new, more in-depth hypotheses and research questions. Consequently, it adds to the body of knowledge concerning the most efficient approaches relevant to this field of study.

The study is the first of a kind to present a perspective of a common methodology and modelling tool for 100% renewable energy (RE) analysis. The discussion presented is believed to be highly instrumental for assessing the practicability and resiliency of transitioning to 100% renewable energy.

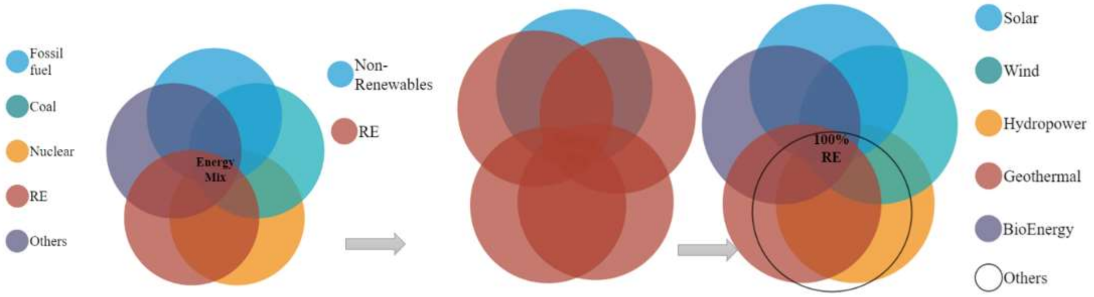
## 5.2 100% RE Concepts

### *5.2.1 Concept Background*

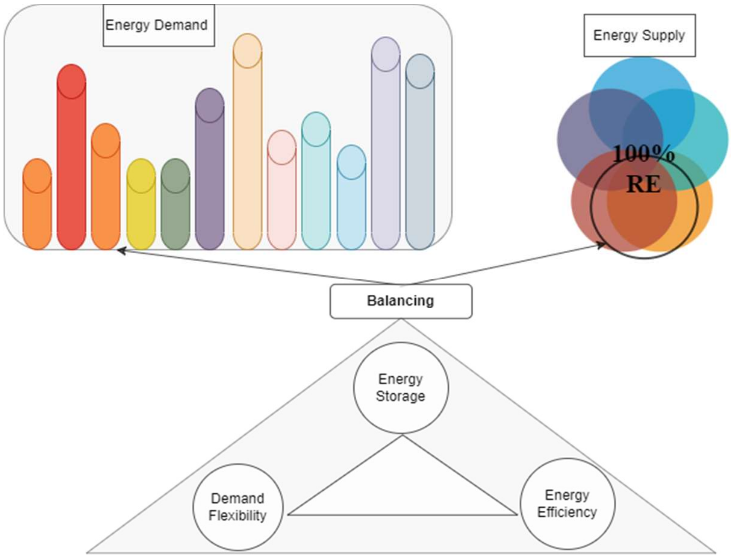
Alongside the main renewable energy sources generally in use, fuel cells, solid waste, and hydrogen energy technologies help meet rising worldwide electricity demand [303]. They increase the promising opinion that all energy usage can come from renewables. Energy storage integration, size, energy flow management, and optimisation can now be examined in wind turbines, solar panels, biomass gasifiers, and fuel cell power plants to add to the present discussion of the possibilities. The process of assessment can be done using a series of approaches and evaluation mechanisms, as well as concepts that suit the needs of the case selected for the studies, but with the overall goal of determining the best options that are available towards the transition into a complete net-zero-carbon-free environment, in this case, a society that completely uses renewables for all it purposes. As a result, interest in developing 100% clean energy systems has increased in recent years [113]. Many leading scholarly journals have published studies on the topic, with a bibliometric review done by S. Khalili and C. Breyer in [304] showing most of the studies that have been carried out.

The term "100% renewable energy" entails that all energy used comes from renewable sources that replenish continuously and have no or minimal environmental impact [304], [305], [306]. One of the foremost 100% RE global studies by Jacobson M. in [112] proposed the possibility of using only hydro, wind, and solar for all purposes in 139 countries due to the abundance of natural resources already identified. By gradually replacing non-renewable energy sources such as coal, oil, and natural gas with renewable energy, societies can reduce global carbon footprints and other pollutants in the drive to mitigate the health and climate change consequences. The transition to 100% renewable energy represents a substantial transition in the global energy sector, seeking to substitute all fossil fuels and other non-renewables with sustainable alternatives, as depicted in Figure 1.

The transition is increasingly noticeable as societies tackle climate change [183], [307], [308], [309] and reduce reliance on finite resources. Renewable technologies, such as solar photovoltaics, wind turbines, hydroelectric systems, and geothermal power plants, have undergone notable advancements such as green energy storage [310], smart grid technologies [311] for the management of energy resources and systems [312], [313], [314], [315], [316], resulting in the integration of renewable sources into existing energy infrastructure and enhanced balancing of energy efficiency, demand flexibility, and RE intermittency availability issues necessary for a sustained 100% RE to occur.



(a). Transitioning into 100% RE



(b). Energy chain balancing with 100% RE

**Figure 5.1.** The 100% RE concept. Source: author’s elaboration**.**

Nevertheless, it is imperative to overcome obstacles and barriers to attain the full feasibility of 100% renewable energy.

### *5.2.2 History of 100% RE Studies*

Table 5.1 presents an overview of the growth in 100% RE research and recognition of such possibilities in the global energy transition.

**Table 5.1**. Historical Path of Key Selected 100% RE Research Progresses

| Year | Protocol and Description | Ref. |
|---|---|---|
| 1975 | Premier Research [1st Ever Studies on 100% RE with Denmark as the Case Study (all RE)]<br>Quantitative study | [73][317], [318], |
| 1976 | 2nd Studies on 100% RE with USA as the Case Study (‘’The Road not Taken”) (all RE)<br>Framework Development | [319] |
| 1993 | Report of the Stockholm Environment Institute for Greenpeace International<br>1st studies/report for 100% RE target for the year 2100 | [320] |
| 1996 | Premier Research<br>1st studies for 100% RE target for the year 2050<br>By Sørensen | [321] |
| 2004 -till date | Most Cited Research Team was established<br>By Lund et al.<br>Premiers many of the 100% RE target studies<br>EnergyPLAN software developed and modified for use in 100% RE target studies | [322][113], [323], [324], [325], [326] |
| 2005 | Premier Research<br>By Czisch<br>1st 100% RE Study on Europe-MENA-Eurasia | [327] |

| | | |
|---|---|---|
| | 1st studies to use multi-node and hourly method in the 100% RE studies | |
| 2009 – till date | 100% RE Studies for 139 countries (wind, water and solar only RE) with complimentary studies<br>By Mark Jacobson, Delucchi et al.<br>100% RE target for 2030 | [111], [112], [306], [328], [329], [330], [331], [332], [333], [334] |
| 2009 | Premier Research<br>By Sterner<br>The conceptual framework developed for Power-to-X to be applied in energy systems studies | [335] |
| 2015 | Recognition of 1993 Greenpeace International report on 100% RE<br>The 1993 Greenpeace report received wider attention in the global energy transition discussions | [336] |
| 2017 – till date | Premier Research<br>By Bogdanov and Breyer<br>Development of the LUT Energy System Transition Model (LUT-ESTM)<br>The research group at LUT, Finland, comprising of Breyer, Bogdanov, et. al.<br>With the use in modelling 145 regions of the world and the entire energy-industry system<br>1st global analysis of the cost reduction potential associated with transitioning to a 100% renewable energy (RE) power sector.<br>Conducted at an hourly resolution and covers 145 regions worldwide<br>1st global analysis of 100% RE using the LUT-ESTM model to demonstrate a cost-neutral transition for the whole regions' (Europe, Eurasia, and MENA) energy system at hourly resolution. | [337][295], [338] |
| 2017 | Premier Research<br>Brown et al.<br>Development and Launch of PyPSA- open-source tools for investigating multi-node energy networks | [339] |
| 2018 | IPCC Acknowledgement of the Stockholm Environment Institute for Greenpeace International Report | [76] |
| 2018 | Fridays for Future (FFF) Movements (School Strike for Climate)<br>Initiated by Greta Thunberg<br>The FFF promotes climate change action with three main goals: transitioning to 100% renewable energy, preventing the further use of fossil fuels, and providing aid to climate refugees | [340] |
| 2021 | Premier Research<br>By Harmsen et al.<br>1st global analysis of a nearly 100% RE using an integrated assessment model | [23] |
| 2022 | Premier Research<br>On the History and Future of 100% RE Research | [305] |
| 2022 | Premier Research<br>1st Bibliometric Review on 100% RE System Analysis | [304] |

| | | |
|---|---|---|
| 2023 | Premier Research<br>1st Research on Rationale and Recommendation for 100% RE in Africa only | [341] |
| 2023 | Premier Research<br>1st Study on Towards a Common Methodology and Tool for 100% Renewable Energy Research and Analysis | Contribution from the chapter of this thesis |

As seen in Table 5.1, there has been a noticeable growth in 100% RE research and acknowledgement. It can be inferred from the changes in the global energy transition policies that have constantly seen energy as a major driver for sustainable development. The progress and growth in 100% RE also seem to provide guiding assurances to develop policies that drive this endeavour. The number of research papers describing 100% renewable energy (RE) systems is presented in Figure 5.2, according to a bibliometric study by S. Khalili and C. Breyer [304].

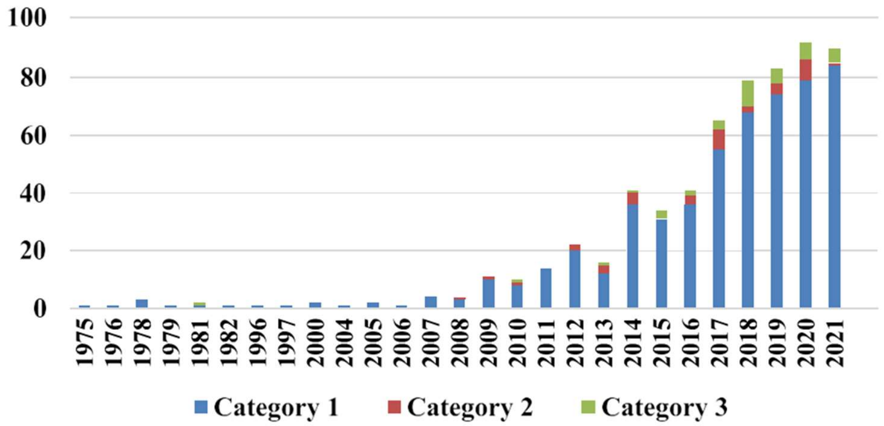


**Figure 5.2.** Trend of 100% RE studies according to S. Khalili and C. Breyer [304]. Note: a particular geographic area is considered in the first category. At the same time, a generic analysis without a specific region's citation falls under category two. The third category is devoted to reviews, which may or may not involve a particular geographic analysis. Since its inception in 1975, Category One has published at least one article annually, on average, according to statistics. Category two was first used in 1996 and has had regular articles since 2008.

In the bibliometric study of more than 600 scholarly articles on renewable energy systems that rely only on renewable sources, it was found that most of the papers were published by or co-authored by certain organizations on a global scale, mainly based in the United States and Europe. The journals Energy and Applied Energy by Elsevier publishers had the highest number of articles and citations. With nearly 1400 published authors and a compound yearly growth rate of 26% in articles, the research offers a comprehensive overview of research spanning over 40 years. S. Khalili and C. Breyer in [304].

Figure 5.3 shows the spread of 100% RE studies per country. In contrast, Figure 5.4 shows the region distribution, inferring that some countries and regions have had more studies by more publications. In contrast, others have none or only a few have carried.

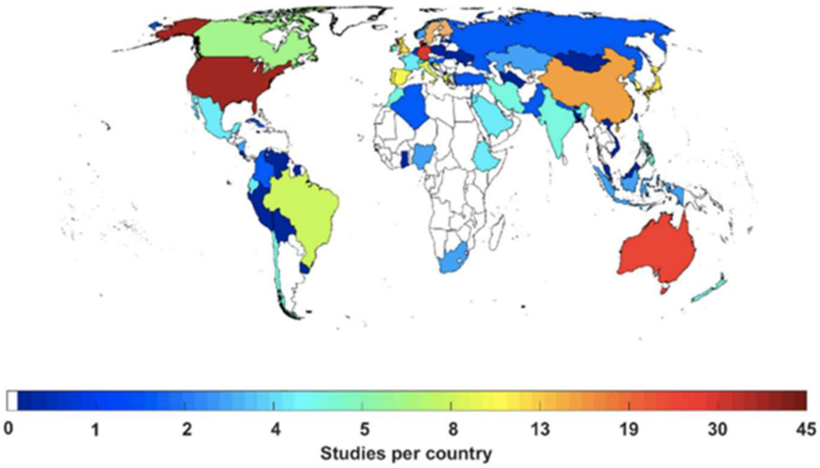


**Figure 5.3.** Distribution of 100% RE studies per country as carried out by S. Khalili and C. Breyer in [304].

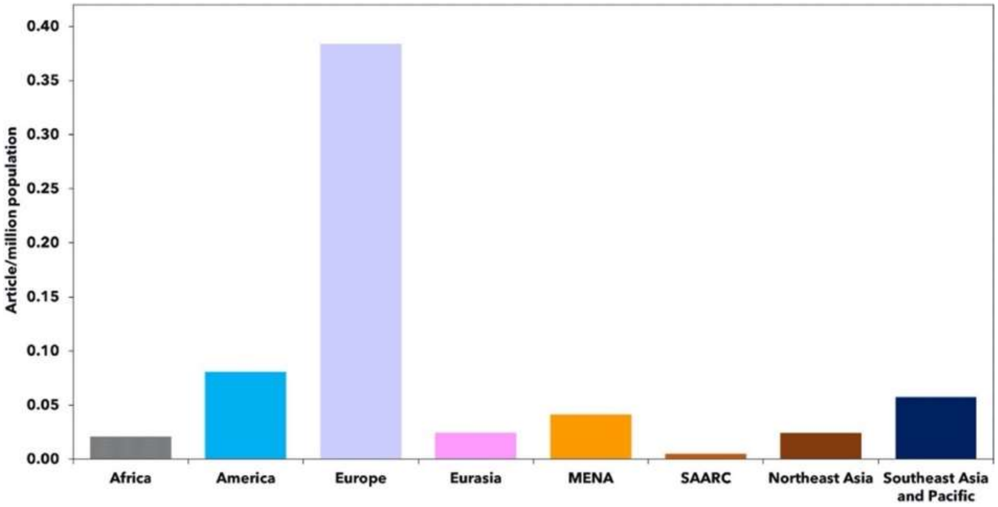


**Figure 5.4.** Distribution of 100% RE studies per region (about 750 studies considered) as carried out by A. S. Oyewo et al. in [341].

Regions such as Africa, Eurasia, SAARC, and North Asia have had very little attention to 100% RE research. Yet, they constitute some of the major $CO_2$ emitters globally [210], and with the envisaged highest population rate now and in the coming year, even beyond 2070, the population of several countries will either peak or already be on a decline [221], [342]. It might infer that there would be an increasing energy demand in these regions/countries and increased $CO_2$ should energy resources in use not be made from renewables.

It is important to note that these 100% RE studies are very useful in providing pragmatic assurances to national/regional policymakers, even though it can be inferred from Table 5.1 that the perception of the 100% RE possibilities at low cost across the globe has not yet been fully acknowledged.

For instance, despite the publication of an initial national pathway in 2012 [343], outlining a goal of achieving 100% renewable energy (RE) by 2060, subsequent scenarios proposing similar objectives or near-complete reliance on RE in several countries [306], [330], [344], [345], [346], [347], [348], [349], [350], [351], [352], [353], [354], [355], [356], [357], [358], [359], [360], [361], [362], [363], [364], [365] have had limited influence on the political discourse [366].

Achieving 100% renewable energy is only gaining traction; however, challenges persist in its integration into global energy transition policies. The complexity of the transition requires significant infrastructure modifications and may incur significant expenses. Additionally, some nations heavily rely on non-renewable energy sources, making a comprehensive and expeditious transition challenging.

### *5.2.3 Significant Approaches Used in Countries with Near 100% RE in its National Grid*

Many countries are deliberating on the strategies to achieve the nation's newly established objective of attaining 100% renewable energy for power generation, prompted by the recent acts of the Russian–Ukraine war. It can be seen that a few countries have already or are close to achieving that, and the approaches that have facilitated such possibilities are highlighted in Table 5.2.

**Table 5.2.** Significant approaches helping some of the countries achieve near-or-complete RE successes. Source: author's elaboration.

| Country | Highlights |
|---|---|
| Iceland | *Geothermal utilisation*<br>With abundant geothermal resources from volcanic activities, Iceland has harnessed geothermal energy for heating and electricity. It has enabled the country to achieve high levels of renewable energy utilisation.<br>*New energy technologies integration*<br>With ample renewable energy sources such as geothermal and hydroelectric, Iceland focuses on energy storage technologies such as pumped-hydro storage to store extra energy during high-generation and release during low-generation times with high demands. |
| Norway | *Hydropower dominance*<br>An abundance of hydropower resources generates a significant portion of its electricity. |

| | |
|---|---|
| | *Excess electricity for hydrogen production*<br>They also utilise their excess renewable energy to produce hydrogen for other sectors, such as transportation.<br>*Taking the global frontier in electric vehicle (EV) utilisation*<br>It is a global leader in EV adoption, reducing its dependency on fossil fuels for transportation. |
| Iceland/Norway | *Regional collaboration and grid interconnections*<br>Nordic countries such as Norway and Iceland, including Sweden, Denmark, and Finland, have collaborated on energy interconnections, enabling them to share excess renewable energy and balance out variations in generation. |
| Costa Rica | *Local community initiatives*<br>They have made significant strides toward renewable energy by involving local communities and focusing on decentralised energy production through solar, wind, and hydropower energy.<br>*Hydropower and geothermal utilisation*<br>They capitalised on their unique geography to harness hydropower and geothermal energy. |
| Uruguay | *Supporting policy regulatory environment*<br>Uruguay's success in renewable energy can be attributed to its stable regulatory environment, enabling the growth of wind and solar energy projects. |
| Ethiopia, Zambia, DR. Congo, Uganda, Kyrgyzstan, Tajikistan, Venezuela, Korea DPR, Angola, Mozambique, Ecuador, Columbia, Lao PR | *Hydropower dominance*<br>Hydropower resources are abundant, helping to generate a significant portion of its electricity from this source. |
| Scotland | *Wind power dominance and supporting policy regulatory environment*<br>Scotland has made progress in using wind power in its grid. Offshore wind farms are a major cause for its renewable energy success. It has invested much in wind power and passed advantageous legislation to promote renewable energy. |

Figure 5.5 shows 30 countries with nearly or 100% RE production from their national mix for RE % in national electricity mix and electricity access by % population and population data (2022), respectively. The latter is represented in Figure 5.6.

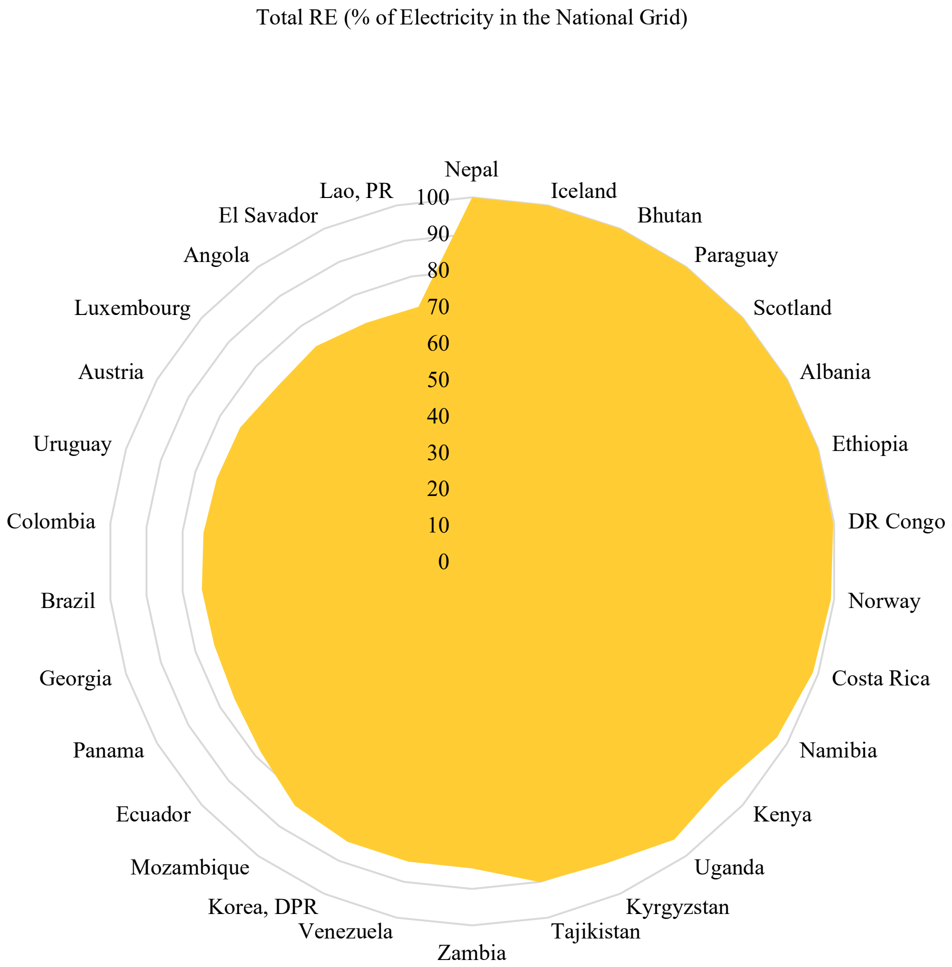


**Figure 5.5.** Countries with near or 100% RE in national electricity mix (70% and above) (data only for RE composition are only from solar, hydro, geothermal, and wind). Data extracted from [90][213].

Countries such as Iceland have already reached their goal of 100% energy production, with about 87% of its primary energy from renewables. Conversely, countries such as Costa Rica (setting most consecutive days for 99% electricity from RE) and Uruguay (about 100% electricity from RE, mainly hydropower) are close to reaching the 100% RE target [90].

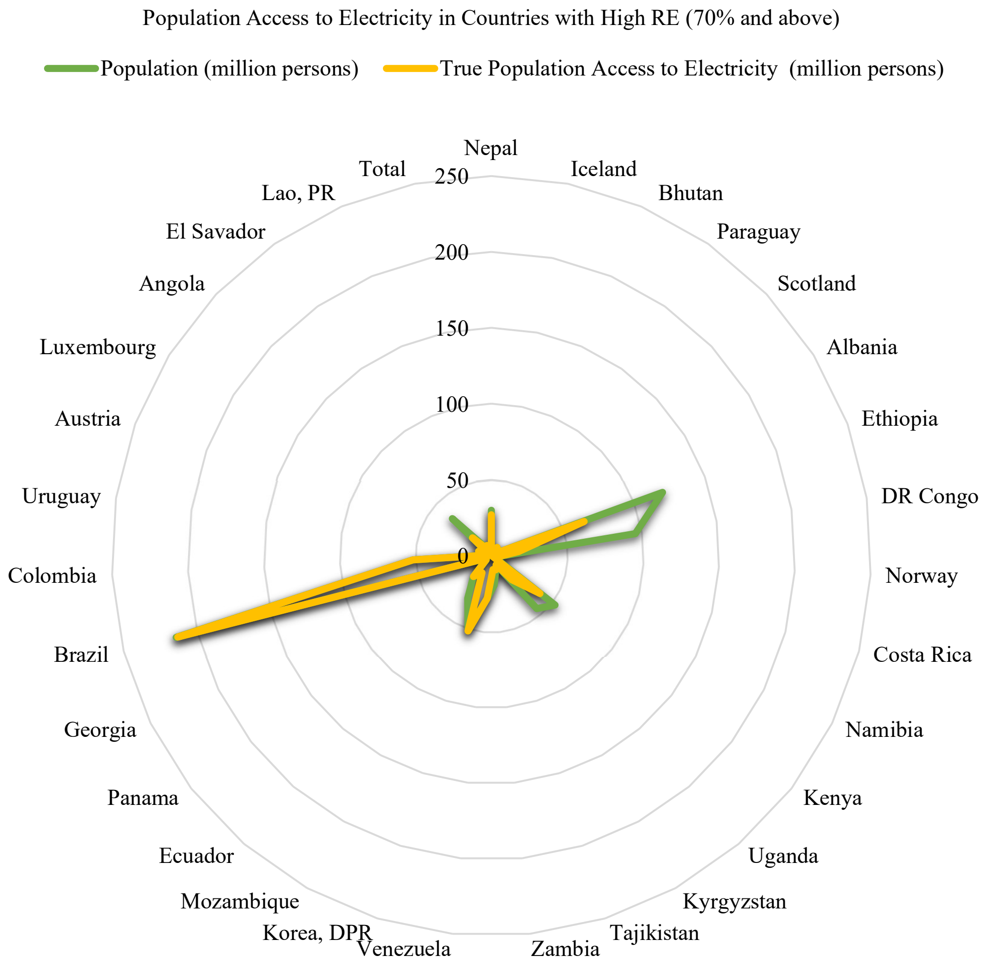


**Figure 5.6.** Population access to electricity in countries with near or 100% RE (70% and above) Data from [90][213].

Despite the progress by several countries, as shown in Figure 5.5, challenges persist from key observations, some of which are that they are either nations with very little population or that the population do not have 100% access to electricity (highlighted in Figure 5.6) or there is an intermittent electricity supply. The countries that emit the highest amount of greenhouse gases through their energy processes are not in any way represented in either Figure 5.5 or Figure 5.6, except for Ethiopia, which is among the top 10 $CO_2$ emitters in Africa. However, numerous nations and institutions have continuously driven to promote renewable energy adoption through policies, research and development, and advocacy.

With the EU RE target highlighted by the IEA report in [367], the Portuguese government has set a four-year goal of increasing renewable energy consumption from 60% in 2021 to 80% in 2026. Natural gas imports have switched from Russia to Nigeria and the United States. EDP, the largest power provider on the Iberian Peninsula, plans to switch to renewable energy by the decade's end. Due to these developments, Portugal will no longer depend on fossil fuels. Offshore wind power generation in the Netherlands is predicted to increase by a factor of two by the end of this decade, making it a leader in Europe's energy revolution. By 2050, the North Sea area hopes to have the capability to generate 150 gigawatts (GW) of power. The United States is still far from its goal of using only clean energy, but it may reap benefits from renewable energy such as wind and solar. By increasing its clean energy production, Denmark hopes to become a top exporter of renewable power. The EAG in Austria plans to invest EUR 1 billion annually and set aside special money for clean technology to achieve its goal of producing 100% electricity from renewable resources by 2030.

Research and policy implementation have led to technological advancements resulting in improved efficiency and cost-effectiveness of renewable energy solutions, making them increasingly appealing. At a critical juncture in the transition, ongoing scholarly inquiry, innovative thinking, and cooperative efforts can make significant strides towards a complete reliance on renewable energy. The discourse among the general populace is particularly intense regarding the non-homogenous global population growth changes in countries, increasing energy developments in developing countries, economic ramifications, and advantages associated with the transition process. The public and political discourse regarding the implications of the ratified Paris Agreement remained relatively limited until additional political pressure was exerted, notably through initiatives such as the Fridays for Future movement (FFF), supported by Scientists for Future [55] [340]. In line with the FFF, additional scholarly investigations have been disseminated, which expand upon preceding research endeavours such as the regional collaborative studies as in [112], [306], [327], [349], [361] and studies in the major global emitters of $CO_2$ like China [350], [368], [369], USA [360][356], India [358], Japan [347], [357], Iran [362], Germany [355], [361], [370], Indonesia [353], Canada [371], [372], South Korea [373], Saudi Arabia [364], [365]. Similarly, the same studies have also been investigated in Africa's major emitters of $CO_2$ as in South Africa [351], Egypt [374], Algeria [375], and Nigeria [346], [348], [376].

Several countries have made substantial progress towards near or 100% renewable energy (RE) through diverse measures. Table 1 highlights how countries have used different approaches to reach near or 100% renewable energy. It involves a combination of policy frameworks and supportive regulations, technologies, market processes, renewable energy investment, energy storage integration, geographical advantages, investments in research and technology development, and strong political commitment and innovative solutions.

As renewable energy evolves, new approaches and successes may arise. It is also vital to highlight that countries' natural resources, technological capability, political context, and socio-economic aspects determine the optimal options. Reaching close or 100% renewable energy success requires a holistic approach that includes several of these tactics, and each country's strategy is unique, so what works for one may not work for another.

Other countries aiming towards 100% RE have used comparable and separate significant measures in addition to the support mechanisms described in Table 1 above. These countries include Sweden, Portugal, Finland, Germany, Denmark, and New Zealand.

Sweden has worked hard to combine renewable energy and cutting-edge energy storage devices. This strategy helps ensure a stable supply of goods and services, especially when renewable energy sources are intermittent. With renewable energy growth, demand-side management and energy efficiency have been introduced in Portugal. The government has successfully used renewable energy with this comprehensive policy. Better grid integration of intermittent renewable sources is achievable with smart grids and demand response systems. After enhancing grid functioning, Portugal ran on renewable energy for 6 days in 2016.

Sweden's politicians have set ambitious renewable energy goals and funded research and development. Biofuels and wave energy converters have received significant R&D funding from Finland. Technological advances such as solar panels and wind turbine efficiency have reduced the cost of renewable energy generation. Energy-efficient technology and practices can help countries satisfy their energy needs with renewables by cutting demand.

Due to the legislative and regulatory structure that guarantees renewable energy producers' regular compensation for their power, usually through a long-term contract, RE's proportion of national electricity supplies has increased. Germany's "Energiewende" (energy transition) strategy pioneered feed-in tariffs (FiTs) and rapid deployment of renewable energy sources such as solar and wind, resulting in a high share of renewables in the energy mix and a decentralised energy system. A policy such as the Renewable Portfolio Standard/Renewable Energy Standard requires utilities to obtain a certain share of their power from renewables. These standards have helped Denmark and Sweden increase renewable energy utilisation. If the public is educated on the benefits of renewable technology, policy adjustments and widespread adoption may receive more support.

Carbon pricing and strict emission reduction objectives help renewable energy transition. New Zealand and Iceland are already doing this. Island states have used international aid and investment for solar and wind power to switch to renewable energy. Community and municipal initiatives have improved renewable energy consumption in certain places. Danish community-owned wind farms and German solar co-ops are examples.

Figure 5.7 presents the RE mix of the 30 countries with near or 100% RE in their national mix. It can be observed that a high share of hydropower appears to be dominant across countries, except for Scotland, followed by a higher share of wind in about 10 countries. The margin of contribution from solar is less than wind but higher than geothermal, which is mainly used in 4 out of the 30 countries. For the same Figure 5.7, the RE mix of four top global $CO_2$ (China, the USA, India, and the EU) is included. Much difference that can be seen is the seeming proportionate share of solar, wind, and hydro in these locations, except for geothermal energy.

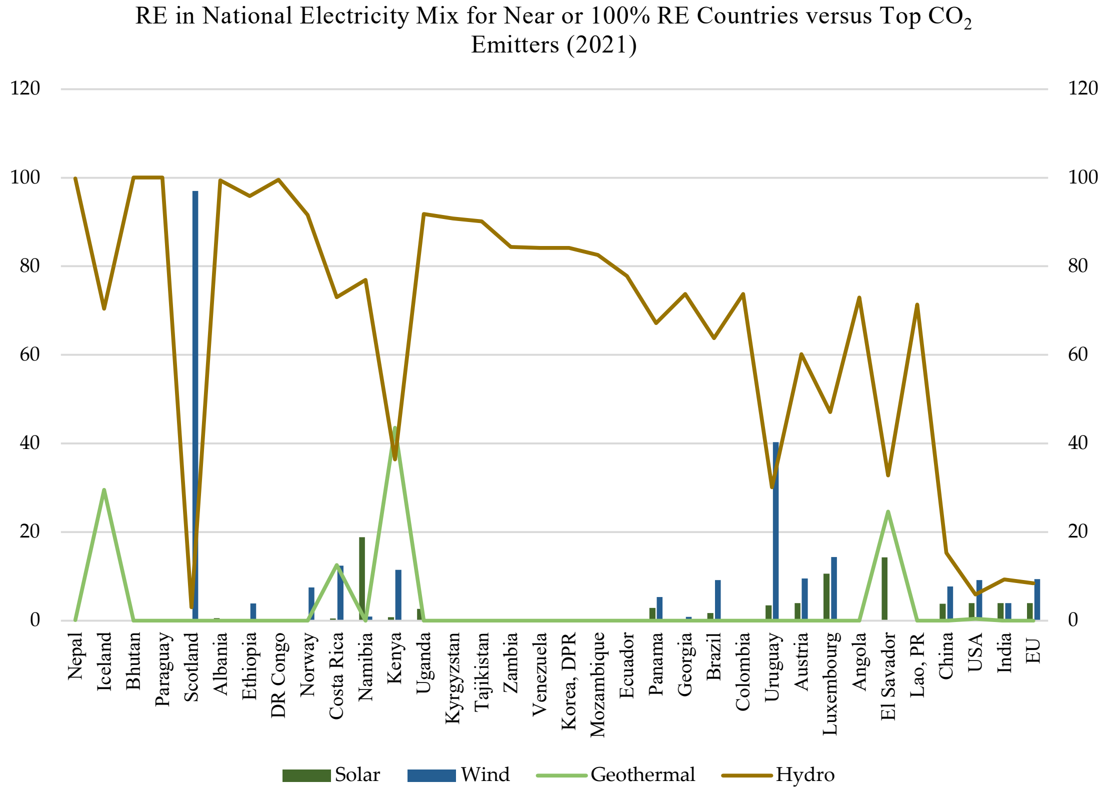


**Figure 5.7.** RE electricity mix in countries with high RE (70% and above), updated from [90][213].

Table 5.3 highlights the categories of the renewable energy systems used in 100% RE studies of different countries (herein, we considered mainly the top global $CO_2$ emitters). Table 5.4 also summarises the studies with the employed support mechanisms and evaluation approaches.

**Table 5.3.** Summary of RE considered in the top global emitters of $CO_2$ 100% RE studies.

| Country | RE Technology Covered in the 100% RE Studies | | | | | | | Target Year | Actual RE % in National Mix (2021) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| | Solar | Wind | Hydropower | Bioenergy | Geothermal | Others | Storage | | | |
| China (1) | - | - | - | - | - | G | - | N/D | 28.91 | [324] |
| China (2) | ✓ | ✓ | - | ✓ | - | - | - | N/D | 28.91 | [377] |
| China (3) | - | - | - | - | - | G | - | 2030 | 28.91 | [378] |
| USA (1) | - | - | - | - | - | S | - | 2050 | 20.74 | [360] |
| USA (2) | ✓ | ✓ | - | - | - | - | - | 2040–2045 | 20.74 | [356] |
| India (1) | - | - | ✓ | - | - | P2X | ✓ | 2050 | 19.38 | [358] |
| India (2) | - | - | - | - | - | - | - | N/D | 19.38 | [354] |
| Europe, Eurasia, and MENA regions | ✓ | ✓ | ✓ | ✓ | ✓ | G | - | 2030 | - | [337] |

✓ refers to the inclusion of the particular RE technology in the study referenced G—grid, P2X—power to X, N/D—not defined. RE% data extracted from [213].

**Table 5.4.** Summary of key 100% renewable energy studies in top global and African $CO_2$ emitters.

| Country | Summary of Studies | Support Mechanisms and Evaluation Approaches Used | Target Year for 100% RE | Climate Scenario | Ref. |
|---|---|---|---|---|---|
| China (1) | One of the earliest experimental projects into 100% RE. This study found China's large domestic RE sources promising, suggesting a 100% RE system analysis for China. | Renewable resource assessment | N/D | No | [324] |
| China (2) | Design optimisation is suggested for improving 100% renewable energy systems in low-density areas. Integration and performance of 100% RES were investigated in 30 Chinese cities with payback times under six years, showing that future breakthroughs could shorten the payback period. | Energy system analysis<br>Design optimisation<br>Economic assessment<br>New technology integration | N/D | No | [377] |
| China (3) | This Beijing study used two-phase energy system models to study Beijing's 2030 energy market reaching 100% RE. The reference scenario uses 72% more primary fuel than the RES scenario 2030. | Reliability and optimisation<br>Environmental assessment | 2030 | No | [378] |
| USA (1) | 100% renewable energy (RE) in US electric power networks were simulated. The least-cost buildout reaches 57% RE penetration in 2050 under base conditions. According to this base scenario, $CO_2$ abatement | Energy system analysis<br>New technology integration | 2050 | No | [360] |

| | | | | | |
|---|---|---|---|---|---|
| | costs of 80%, 90%, 95%, and 100% RE are USD 25, USD 33, USD 40, and USD 61/ton, with system costs rising from USD 30 to USD 36/MWh at 95% (achieved in 2040) and USD 39/MWh at 100%. | Economic assessment<br>Environmental assessment | | | |
| USA (2) | New Mexico, a US state with great solar and wind potential, is used in this study. An optimisation problem is proposed to determine the amount of renewable generation and energy storage needed to balance 100% of a utility's hourly electricity demand over several years at a desired cost. | Energy system analysis<br>Renewable resource assessment<br>Design optimisation | 2040–2045 | No | [356] |
| India (1) | The model optimises the least cost combination of RE power plants and storage technologies to create a completely RE-based power system by 2050 based on 2015 installed power plant capacities, lives, and total energy demand. The levelized cost of electricity would fall from EUR 58/MWhe to EUR 52/MWhe in 2050, enabling a 100% renewable energy system. | Energy system analysis<br>Economic assessment | 2050 | No | [358] |
| India (2) | Delhi's 100% renewable energy system's technological and economic potential is examined in this study. Delhi may promote a regional energy transition by reducing primary energy by 40%, energy costs by 25%, greenhouse gas emissions, air pollution, and health costs. | Energy system analysis<br>Renewable resource assessment<br>Economic assessment<br>Environmental assessment<br>Energy–environment–economy development | N/D | No | [354] |
| Europe, Eurasia, and MENA regions | This study explored the feasibility of a regional integrated renewable energy-based carbon-neutral power system using existing energy generation, storage, and transmission technologies throughout Europe, Eurasia, the Middle East, and North Africa. With a total LCOE of about EUR 42/MWh, the result showed that the integration could produce an economically viable and sustainable energy system less expensive than coal-CCS or brand-new nuclear options, helping improve stability flexibility and lessen the need for energy storage. | Economic assessment<br>Energy system analysis<br>Renewable resource assessment | 2030 | No | [337] |
| Japan (1) | The research designed and evaluated a renewable energy system for Akita, Japan. Wind power potential is estimated at 35.2 TWh/year, greatly above the 11.3 TWh/year electricity need. Batteries must have 48.4 GWh to meet yearly demand for over 1000 h. Batteries produce hydrogen, cutting electricity costs by 57% and overall costs by 32%. | Renewable resource assessment<br>Economic assessment<br>New technology integration | N/D | No | [357] |
| Japan (2) | Akita prefecture's 100% renewable energy system's biomass power cost and availability are examined in a second study [43]. Batteries met demand when other energy sources failed. The "no biomass", "supply shortage", and "baseload" situations were explored. Compared to "no biomass" electricity prices, "baseload" lowered them all. | New technology integration<br>Economic assessment | | No | [359] |
| Japan (3) | Japan's renewable energy future using a 40-year hourly energy balance model was examined. Under restrictions, differential evolution finds the | Renewable resource assessment | 2050 | No | [347] |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | lowest-cost solution. Japan has 14 times more solar and offshore wind resources than needed for 100% renewable electricity, and solar costs USD 86/megawatt-hour and wind USD 110. Japan can be power self-sufficient at competitive prices despite solar photovoltaic and offshore wind deployment constraints. |  |  |  |  |
| Germany (1) | The study tried to clarify the possibility of Germany's 100% renewable energy transition in 2050. Consumption changes to Germany's heating, industrial, transport, and power sectors' energy systems were made using renewable resource potential, energy system costs, and primary energy supply. This change is feasible technically and economically, but it requires action to implement it efficiently and affordably. | Energy system analysis<br>Renewable resource assessment | 2050 | No | [355] |
| Germany (2) | This research examines Germany's 100% renewable and sector-coupled energy system's viability. OSeEM-DE, an hourly optimisation tool, uses open energy modelling to study the German energy system. Volatile generators cost EUR 17.6–26.6 billion annually, and heat generators cost EUR 23.7–28.8 billion annually. Parametric scenarios affect investment capacities and component costs. The model recommends EUR 2.7–3.9 bn/yr for power and heat storage. According to sensitivity analysis, storage and grid expansion maximise system flexibility and lower investment costs. | Energy system analysis<br>Economic assessment<br>New technology integration<br>Energy financing<br>Reliability and optimisation | N/D | No | [370] |
| Iran | The report forecasts the possibility of 100% renewable in Iran by 2050. Iranian electricity capacity demands from 2015 to 2050 were simulated hourly. It estimates that renewable energy (RE) would supply 100% of the world's power at EUR 41–47/MWhe by 2050, while EUR 32–40/MWhe is unfeasible unless the target time is extended. | Energy system analysis<br>Economic assessment<br>New technology integration | 2050 | No | [362] |
| Canada | This article evaluates the infrastructure costs for transitioning to carbon neutrality for Canada's 10 provinces until 2060. It finds that most of Canada's provinces stand to benefit from a pan-Canadian energy transition by capturing fossil fuel savings. | Energy system analysis<br>Economic assessment<br>New technology integration<br>Environmental assessment | 2060 | No | [371] |
| South Korea | The research develops a renewable energy forecasting model using Korean energy policy as a case study. It analyses four renewable energy scenarios using deep-learning-based models to anticipate power demand and generation. The lowest economic–environmental costs, steady electricity for demand, and 100% renewable energy come from an integrated gasification combined cycle, onshore and offshore wind farms, solar power plants, and fuel cell facilities. | Energy system analysis<br>Economic assessment<br>New technology integration<br>Environmental assessment<br>Policy and regulatory assessment | Annual | No | [373] |
| Indonesia | This study investigates Indonesia's 2050 100% renewable energy power system transition. TIMES' least-cost optimisation analysed 27 power | Energy system analysis<br>Economic assessment | 2050 | No | [353] |

| | | | | | |
|---|---|---|---|---|---|
| | plants and 3 energy storage systems utilising 24 h time slices and hourly demand and supply operational data. It found that nuclear and solar PV utility scale would supply 16% and 70% of electricity output and require USD 95 billion and 215 million tons of $CO_2$-eq. Nuclear-free power increases solar PV utility-scale and battery capacity, land requirement, supply variability, and energy production cost by 9.7%. | New technology integration<br>Environmental assessment<br>Energy–environment–economy development<br>Reliability and optimisation | | | |
| Saudi Arabia (1) | This research indicates that by combining the electricity and growing desalination sectors, Saudi Arabia can achieve a 100% renewable energy power grid by 2050. By 2040, solar photovoltaics would account for 79% of power output, bringing the system's LCOE down to EUR 41/MWh. Since the integrated scenario uses less battery storage and power-to-gas plants, it lowers annual levelized costs by 1% to 3%. | Energy system analysis<br>Economic assessment<br>New technology integration | 2050 | No | [365] |
| Saudi Arabia (2) | As a follow-up to the first Saudi Arabia 100% RE study in [51], the new study presents that a full transition to renewable energy can be possible if single-axis tracking PV and battery storage are the system's primary LCOE drivers. By 2050, if about 79% of all electricity would be produced by PV systems using only single-axis tracking, 441 of power could come from battery storage. Decreasing capital expenditures allows desalination facilities to adapt to changing conditions more quickly. | Energy system analysis<br>Economic assessment<br>New technology integration | 2040–2050 | No | [379] |
| South Africa | South Africa's energy transition is simulated hourly until 2050. The findings imply that solar PV and wind energy can replace coal in electricity. The Best Policy Scenario raises electricity-levelized costs somewhat, while the Current Policy Scenario raises them dramatically. The Best Policy Scenario has 25% lower electricity bills than the Current Policy Scenario without GHG emissions. The cheapest renewable energy system eliminates new coal and nuclear power plants and steadily reduces fossil fuel capacity. | Policy and regulatory assessment<br>Economic assessment<br>Environmental assessment | 2050 | No | [351] |
| Egypt | Egypt's wind energy potential is understudied, so the author examined two 300 MW wind farms for roughness factor and wind power density. Kharga and Dakhla South wind farms can generate 1130 GWh annually with good capacity factors and low electricity costs, lower than the country's needs. Further investment in these wind farms can help Egypt and Southern Europe completely reduce fossil fuel dependence by exporting. | Renewable resource assessment | Annual | No | |
| World | Contribution of this thesis based on the simulation of section 5.3 | Policy and regulatory assessment<br>Environmental assessment | 2100 | Yes | This Chapter |

N/D—not defined.

In addition to the discussion in Section 5.2.2, the next section presents the global simulation of the transition into 100% renewable energy using two evaluation approaches: policy/regulatory assessment and environmental assessment (only global temperature levels).

## 5.3 Towards Achieving 100% Renewable Energy Supply versus the Climate Scenarios: Perspective Demonstration using EN-ROADS Model

### *5.3.1 Overview*

Within a strong climate policy framework, climate scenario targets should be aligned with exploiting renewable energy goals. In this section, the feasibility of implementing a global 100% renewable energy system is analysed in comparison with the long-term climate change scenarios using the EN-ROADS integrated assessment framework based on systems dynamics principles of cause and effect. For the years 2023-2100, four different energy policies are hypothesized: baseline path (BP), optimistic path (OP), more optimistic path (MOP), and extreme optimistic path (EOP) policies, which are explained in the subsequent discussion. This section aims to overcome gaps between existing studies and studies on developing 100% renewable energy global systems. For instance, when using energy modelling tools to analyse a 100% renewable energy system, a comparison of future energy supply and production with climate scenarios is scarcely done. Hence, this section makes the following significant contributions:

1. It provides an insightful perspective for integrated modelling and a simplified framework for future evaluation of the most cost-effective energy transition pathways, including when and how the transition to a 100% renewable energy system.
2. The simulation model of EN-ROADS was used to investigate the feasibility of a 100% renewable energy mix based on global exogenous and endogenous assumptions.
3. Four scenarios are developed, including baseline path (BP), optimistic path (OP), more optimistic path (MOP), and extreme optimistic path (EOP) policy scenario in a single EN-ROADS model. These scenarios are used to compare both renewable energy and fossil fuels targets with other sectors (transport, buildings, industry), growth, emissions, and emissions removal technologies, providing insights that could aid policymakers in developing renewable energy policies that are consistent with climate scenario targets.

### *5.3.2 Model Set-Up in EN-ROADS*

Many different types of energy consumers and producers, including those in the industrial, commercial, residential, and agricultural sectors, have been accounted for in the EN-ROADS model, as shown in Figure 5.8. The data flow used in this study is shown in the schematic diagram of Figure 5.9, which incorporates the four key sectors that heavily drive $CO_2$ emissions towards the complete integration and transition into 100% RE. Figure 5.8 depicts the architectural framework of the EN-ROADS energy transition.

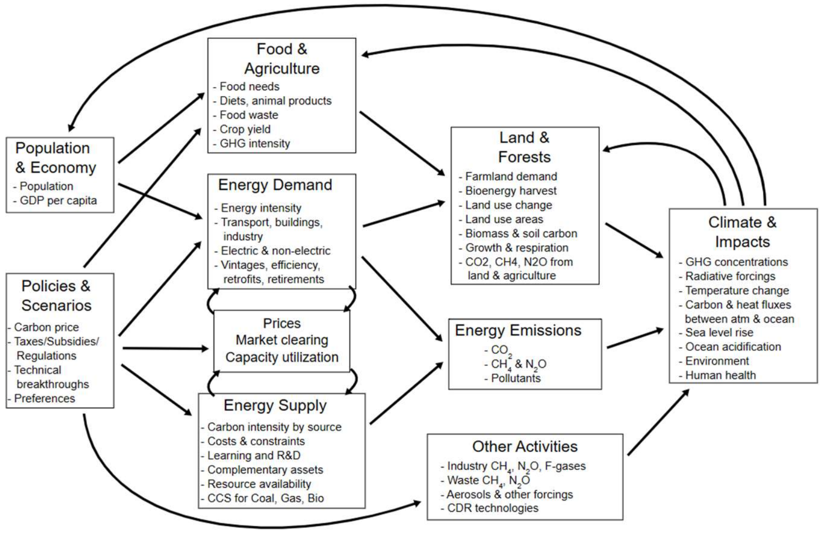


**Figure 5.8.** The general model of Energy-Emissions-Climate with EN-ROAD [380].

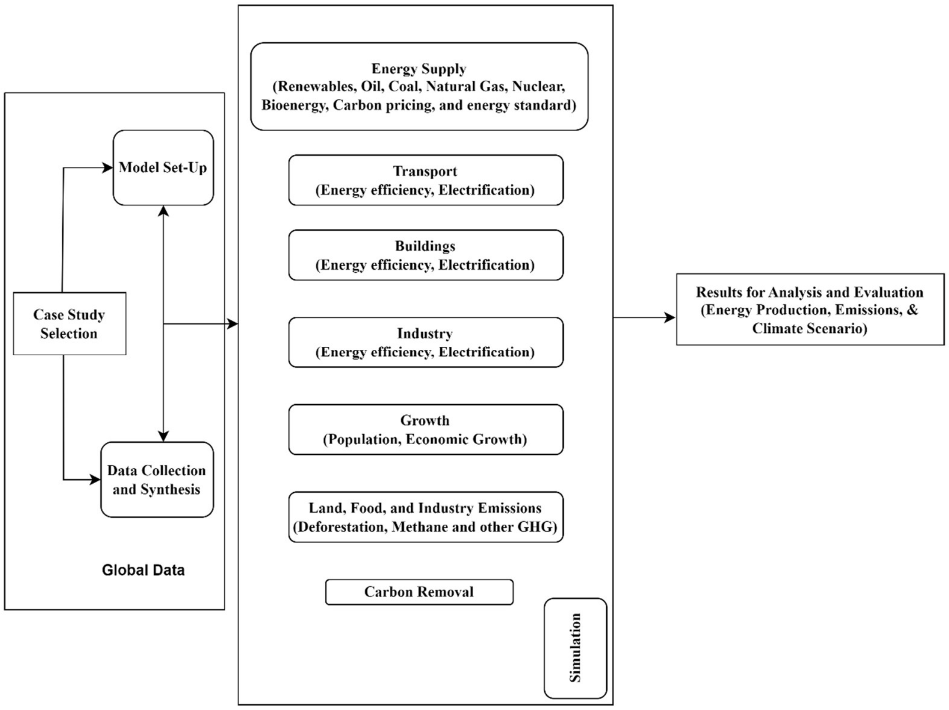


**Figure 5.9**. The EN-ROADS model from input-output. Source: Author's elaboration.

$$\boldsymbol{T_E} = f\ (E_S,\ T_{ee},\ B_{ee}, I_{ee},\ G_{p,GDP}, LFI_e,\ C_r) \qquad (2.14)$$

From Figure 5.9, the transition into 100% RE is studied against the effect on global temperature levels $\mathrm{T_E}$ using variable input data from sectoral contributions (power, i.e., energy supply, transport, buildings, industry), growth, emissions, and emissions removal technologies based on equation (2.14). Where $\mathrm{E_S}$ is energy supply from all the energy sources (Renewables, Oil, Coal, Natural gas, Nuclear, and Bioenergy). $\mathrm{T_{ee}},\ \mathrm{B_{ee}},\ \mathrm{I_{ee}}$ are electrification and energy efficiency for transport, building, and industry sectors, respectively. $\mathrm{G_{p,\,GDP}}$ growth in population and GDP. $\mathrm{LFI_e}$ is the land, food, and industry emissions, while $\mathrm{C_r}$ is the $\mathrm{CO_2}$ removal rate.

The change across these sectors, coupled with growth in population and the GDP, determines the amount of $CO_2$ ($\mathrm{CO}_2\ atm$) that goes into the atmosphere. The relation is computed using the most used mathematical identity by IPCC in emission computation; the Kaya Index is expressed as in equation (2.15).

$$\mathrm{CO}_2\ atm = P * \frac{GDP}{P} * \frac{E_i}{GDP} * \frac{\mathrm{CO}_2\ atm}{E_i} \qquad (2.15)$$

Where P is the population, GDP is the expression of economic growth, and $E_i$ is the intensity of energy from across the different energy sources based on production and anticipated consumption. The temperature values can then be computed using the equations (2.16) and (2.17) below.

$$CO_2 = \frac{\mathbf{CO_2\ atm}}{\mathbf{CO_2\ pre\text{-}industrial\ atm}} \qquad \text{same as (1.7)} \qquad (2.16)$$

$$\boldsymbol{T_E} = \frac{\boldsymbol{\kappa}}{\boldsymbol{\lambda}} * \frac{\boldsymbol{In}\,\left(\frac{\mathbf{CO_2\ atm}}{\mathbf{CO_2\ pre\text{-}industrial\ atm}}\right)}{\boldsymbol{In}\,(\mathbf{2})} \qquad \text{same as (1.8)} \qquad (2.17)$$

Where $\boldsymbol{\lambda}$ and $\boldsymbol{\tau}$ are climate feedback parameters and heat transfer constant, already explained in Chapter 3 alongside equations (1.7) and (1.8), respectively.

The EN-ROADS model is utilized for the global transition research from 2023 to 2100 in 1-year time steps. The model primarily optimizes energy system parameters under constraints and assumes future average global temperature rise and $\mathrm{CO_2}$ emissions. However, this study is also interested in the energy mix that drives this output of global temperature rise and emissions. Hence, the energy mix result is also evaluated to allow the understanding of what amount of energy per technology and the value of renewables needed to achieve the desired climate scenarios. The main usefulness of EN-ROADS over other models is that it offers transition pathways that allow for the iteration of different policy scenarios and strategies to simulate and obtain results based on equation (2.14). The post-processing of simulation results is also performed to make the comparison. Other advantages and limitations of the EN-ROADS are discussed later in this Chapter in section 5.5.

### *5.3.3 Assumptions in the EN-ROADS Model*

a. Scenario Selection

In order to properly examine the potential transition pathways, four scenarios were introduced and considered. The following provides a detailed summary of these scenarios:

i. Baseline Path Scenario:

This scenario assumes that the current energy policy and mix would continue and continuous heavy reliance on imported fossil fuels, particularly coal and natural gas, for electricity generation. The renewable sector would also play a role, but the production of energy from renewable would be slow. In the BP scenario, little or no tax on Carbon causes slow improvement in energy efficiency and electrification at the present status quo. As a result, and without Carbon removal technologies, $CO_2$ emissions from the energy sector are expected to continue to rise.

ii. Optimistic Path Scenario:

This scenario assumes the implementation of policies (medium Carbon tax, less energy efficiency improvement, less electrification, and subsidized utilization of Carbon removal technologies) which aim to increase the share of renewable energy in the global energy mix. By 2050, the policy aims to generate 50% of global primary energy from renewable sources and with at least a share of 3% in energy storage. Hence, a significant increase in the deployment of solar, wind, and biomass power plants would be required. In order to achieve these targets, the policy also calls for the retirement of all coal, nuclear, natural gas, and oil-based power plants after 2030 and an increase in energy efficiency, at least by a factor of 2.5.

iii. More Optimistic Path Scenario:

This scenario assumes that the world would implement the IPCC recommendation of keeping the global temperature less than 2°C, which aims to reduce energy production from fossils by 45%, increase renewables share by 55%, and with at least a share of 3% in energy storage. The energy efficiency is expected to increase by at least a factor of two, and high electrification is achieved. Widespread adoption of energy-efficient technologies and practices across all sectors of the economy is essential. By reducing energy consumption through high energy efficiency of at least 3, the burden on the electricity grid would be eased, and there would be less need to build new power plants.

iv. Extreme Optimistic Path Scenario:

This scenario assumes that the globe would achieve 100% of the primary energy from the combination of renewable energy and energy storage, which aims to reduce the emissions of $CO_2$ to net zero. This scenario is highly ambitious and would require widespread adoption of energy-efficient technologies with an increase in energy efficiency by at least a factor of 4 and very high electrification across all sectors of the economy. By reducing energy production from fossil-based fuels, the burden on the atmosphere and climate would be eased.

A summary of the different scenarios is compared and presented in Table 5.5 below.

**Table 5.5.** Comparison of the scenarios. Source: author's elaboration**.**

| **Scenario** | **Variables Specifications** | **$CO_2$ Emissions** | **Renewables Subsidy** | **Growth in Renewables Share** |
|---|---|---|---|---|
| Baseline path (BP) | Table B1 | High | None | Business-as-Usual |
| Optimistic path (OP) | Table B1 | Low | Moderately subsidized | Approximately 50% |
| More Optimistic path (MOP), | Table B1 | Lower | Highly subsidized | Approximately 55% |
| Extreme Optimistic path (EOP) | Table B1 | Negative emissions | Very highly subsidized | Approximately 100% |

b. Key Input Parameters with Explanation of Assumptions Used in the EN-ROADS model.

The simulation of the transition in this study based on the EN-ROADS model involves primarily four main categories of techno-economic and socio-economic parameters: tax/subsidy in future electricity generation technologies, technologies breakthroughs, reduction in non-renewable energy infrastructures, carbon pricing, energy efficiency, electrification, population/economic growth, afforestation/deforestation, and Carbon removal. These strategies are presented in Table B1 with the corresponding indicators. The techno-economic and socio-economic elements are taken into consideration to anticipate energy consumption, production, carbon dioxide emissions, and climate scenarios. The input parameters per module are described in Table B2.

The energy supply module uses synthetic data as the baseline input to compute energy demand, considering past trends in the production, demand, and consumption of coal, oil, natural gas, bioenergy, nuclear power, and renewable energy sources, as in Figure 2.2 [43], [69]. The cost of various energy sources has a significant influence on decisions about energy infrastructure [381]. Hence, the cost of coal directly affects investments in new capacity, while the cost of oil directly affects investments in new drilling operations and refineries. Additionally, bioenergy sources are subject to distinct subsidies or taxes. The renewables indicator monitors the duration of wind and solar installations as they go through various phases [382], whereas nuclear power plants monitor the phases of their development up to energy production and emerging environmental justice issues [383].

The carbon price extracted from the World Carbon Pricing Database [384] shows that Carbon price exclusively impacts the emissions of carbon dioxide originating from energy sources. To modify emissions other than the baseline values (plotted in Figure A7), managing the deforestation and afforestation indicators influences the changes. The cost of coal, oil, and building energy-efficient energy systems would directly impact emissions from transportation, construction, and industrial activities. However, enhancing the energy efficiency of buildings and industries would progressively reduce emissions by considering the collective average of all infrastructure [385], [386].

Emissions removal technologies play a vital role in mitigating greenhouse gas emissions, while the net $CO_2$ removals are diminished compared to the total removals owing to the natural processes of decay and forest fires in older or diseased forests. The maximum capacity for technical carbon removal is determined by the median value of the ranges shown in the 2018 'Greenhouse gas removal' research conducted by the Royal Society [387]. The primary factor that influences the financial appeal of electric cars and related infrastructure is the integration of transport electrification. The model framework also monitors the total efficiency, encompassing the modification of existing assets.

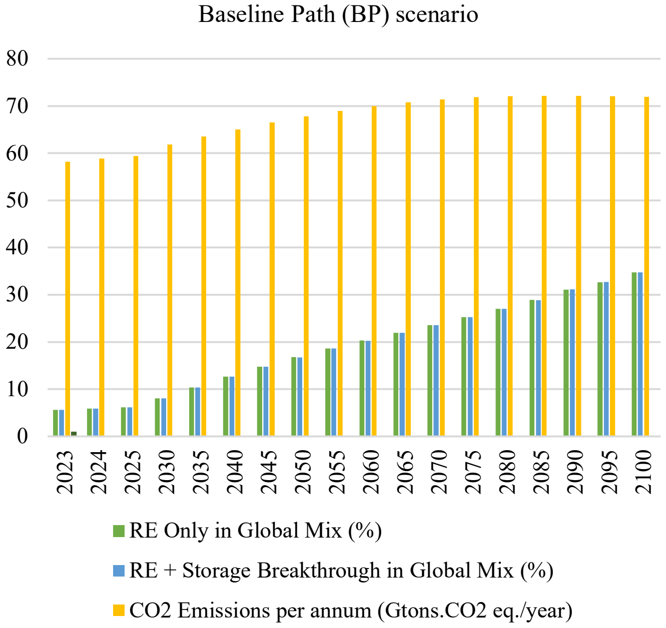
Economic growth is a significant consideration in the En-ROADS model, as it predicts that the GDP per capita growth in all regions would gradually align with a sustainable long-term economic growth rate of at least 1.5% per year, plotted in the Appendix, Figure A8. The model considers the influence of climate change on GDP, resulting in a long-term growth rate in the Baseline Scenario that is below 1.5% per year. The calculation of total global GDP, also known as Gross World Product, involves multiplying the population (data from the United Nations World Population Prospects in [388] and plotted in Figure A9) by the economic growth rate, which is measured by GDP per capita.

### *5.3.4 Simulation Findings*

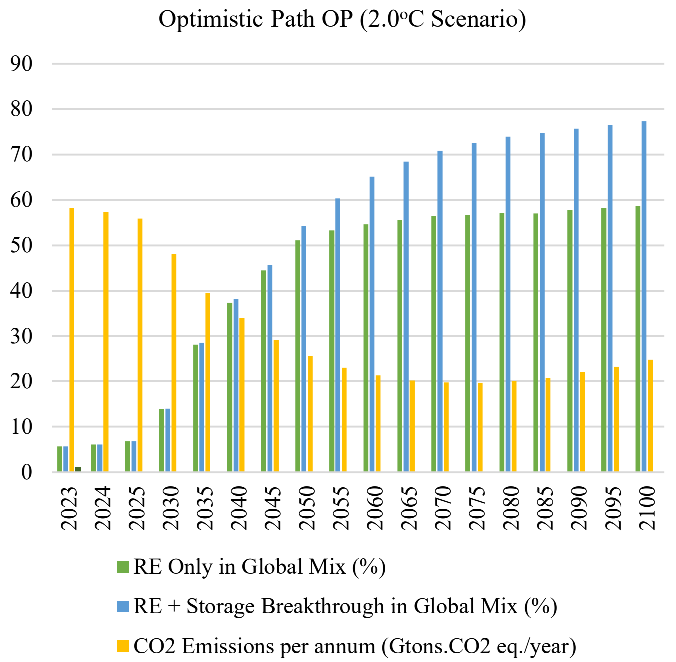
From 2023 to 2100, the results estimate the global primary energy mix by technology under the four scenarios, as well as the $CO_2$ emissions and the corresponding changes in the average global temperature level by 2100. The profile of the energy resource per technology is in the Appendix, Figures A10, A11, A12, and A13 for all four scenarios, where the projection of energy production based on the BP, OP, MOP, and EOP scenarios are such that the energy mix is continuously being dominated by renewables, less reduction in the contribution from bioenergy, and with diminishing production from fossil-based fuels and non-renewable technologies such as coal, oil, and, natural gas.

More importantly, the objective of this section is to discuss the renewable energy share, $CO_2$ emissions, and the average global temperature levels for the four scenarios. Hence, Figure 5.10 (a) – (c) depicts the summary of the values at a 5-year interval, wherein the BP, OP, MOP, and EOP scenarios, the share of renewable energy production continues to increase. In the BP scenario, the share of storage breakthroughs is negligible; hence, RE share is almost the same as RE + Storage, whereas, in the OP, MOP, and EOP scenarios, storage capacity in the global mix increases annually and significant changes are observed from 2040. RE production in the global primary mix would reach 34.69, 77.3, 82.82, and approximately 100% for the BP, OP, MOP, and EOP, respectively, by 2100. A unique result is seen in the EOP, where the global energy mix reaches 99% in 2070 and approximately 100% in 2090 (also shown in Table 5.8), but with a greater increase in the value of ratio storage breakthrough to RE production. The significance of this result shows that the promotion of energy storage is very instrumental to the 100% vision, as the resources for RE production are within limits. These limits, such as biophysical and socioeconomic constraints, have been discussed extensively in the MEDEAS WILLIAMS model of the LOCOMOTION projects of the European Union [389].

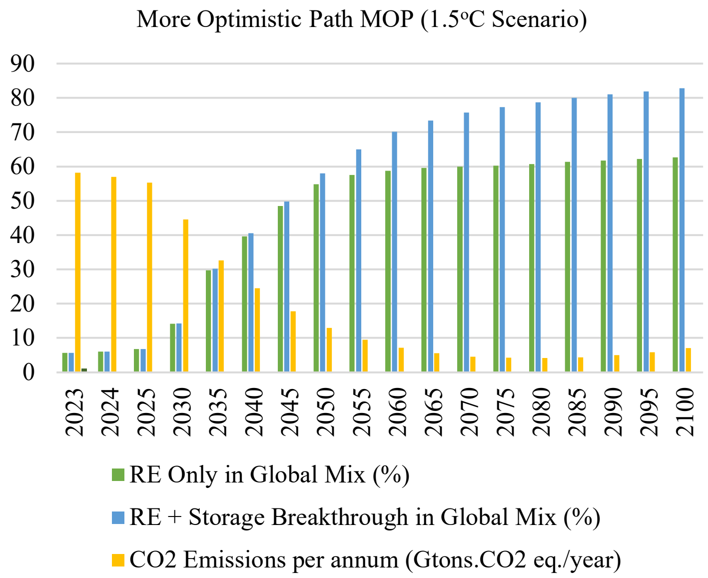
In terms of the $CO_2$ eq emissions, the BP scenario continues to see an increasing emission, with a peak at 72.19 Gtons $CO_2$ eq around 2085, a year where the world's population is expected to peak, as shown in the Appendix, Figure A9 (a), and the developing countries may as well reach a high height of advancement in terms of 100% electrification and urbanization (inclusive of industrial process, transport, and building). However, with the introduction of policies as in the OP, MOP, and EOP scenarios to support RE production, $CO_2$ emissions reduce across these three scenarios but rise again between 2070 – 2085 for all three scenarios. The sudden rise is a result that the existing RE infrastructures are expected to exceed their useful life, hence, the extraction of material and development of newer infrastructures would be needed, giving rise to additional rise to $CO_2$ emissions. Such an occurrence could be avoided if there were technological breakthroughs in industrial processes that allow the production of RE infrastructures with a net-zero Carbon footprint. Most of these technologies are still at infantry and have been highlighted in Chapter 2, Table 2.11 of this thesis. Interestingly, in the EOP scenario, negative emissions are obtained, which is quite good for reaching a very safe climate scenario. However, it is important to see that this may pose a threat to the plant ecosystem, and if such a path is to be followed, measures are considered to address the impact of negative $CO_2$ emissions on the plant ecosystem and other important areas that use $CO_2$ as feedstocks.



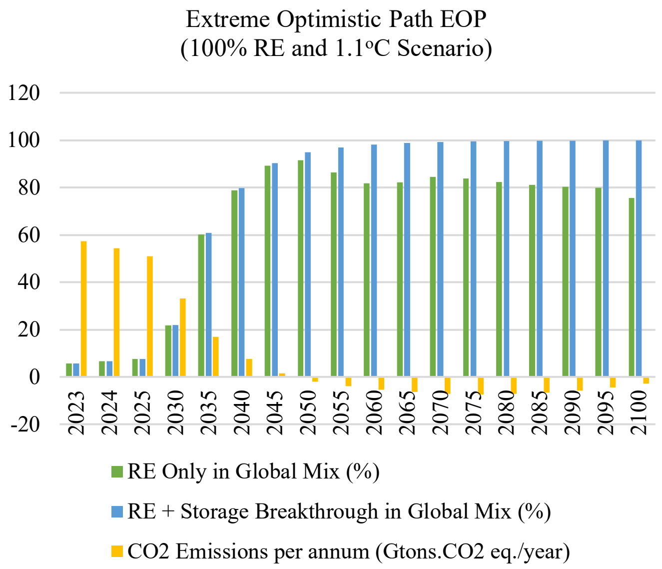
(a). Baseline path.



(b). Optimistic path.



(c). More optimistic path.



(d). Extreme optimistic path.

**Figure 5.10.** Towards 100% RE versus temperature rise level: scenario results.

**Table 5.6.** Renewable energy production (% of total extra joules/year) comparison of the scenarios. Source: author's elaboration.

| Scenario | Temperature (°C) | 2030 | 2050 | 2070 | 2100 |
|---|---|---|---|---|---|
| BP | 3.32 | **8.02** + *0*<br>(644.72) | **16.79** + *0*<br>(759.73) | **23.56** + *0*<br>(872.99) | **34.69** + *0*<br>(1072.14) |
| OP | 2.0 | **13.89** + *0.1*<br>(524.31) | **51.05** + *3.18*<br>(541.53) | **56.34** + *14.45*<br>(673.29) | **58.57** + *18.74*<br>(1057.26) |
| MOP | 1.5 | **14.12** + *0.1*<br>(520.29) | **54.82** + *3.18*<br>(540.24) | **60.01** + *15.7*<br>(708.4) | **62.68** + *20.14*<br>(1147.19) |
| EOP | 1.1 | **21.89** + *0.11*<br>(411.32) | **91.60** + *3.29*<br>(1360.09) | **84.45** + *14.74*<br>(3604.54) | **77.51** + *22.49*<br>(8850.54) |

* Blue (% of total energy production from RE into the global primary mix), Green (extra joules, storage in the global primary mix), and Red (extra joules, energy for storage + total energy production or global primary production).

Overall energy production (in extra joules) is expected to rise continually across all four scenarios, as shown in Table 5.6. However, the increasing amount of production does not follow the same trajectory, as different decision choices have influenced this outcome. For instance, in the BP scenario, no storage breakthroughs are considered. Hence, high extra joules are expected due to continue fossil-fuel burning, which uses high energy intensity to produce power compared with the OP scenario. Because of the high energy intensity, the climate change potential of the $CO_2$ emitted is high, resulting in a 3.32 °C temperature, based on the model structure of the simulation tool.

In the OP, MOP, and EOP, where storage is considered, energy production (in extra joules) increases with increasing storage capacity in the global primary mix. The increased extra joules can be attributed to the fact that additional electricity is needed to produce energy for storage. Since these extra joules would come from the high RE production share, the climate change potential of the energy intensity is reduced, resulting in the corresponding 2.0, 1.5, and 1.1°C temperature levels for the OP, MOP, and EOP, respectively. By incorporating energy storage, a drop in carbon emissions through a decrease in continuous energy production can be achieved. However, such possibilities would come at a very high cost of tax to the population or government subsidy.

**Table 5.7.** Emissions (Gton/eq.) comparison of the scenarios. Source: author's elaboration**.**

| Scenario | Temperature (°C) | 2030 | 2050 | 2070 | 2100 |
|---|---|---|---|---|---|
| BP | 3.32 | 61.83 | 67.83 | 71.37 | 71.93 |
| OP | 2.0 | 48.09 | 25.5 | 19.73 | 24.82 |
| MOP | 1.5 | 44.55 | 12.95 | 4.68 | 7 |
| EOP | 1.1 | 33.19 | -1.98 | -7.08 | -2.77 |

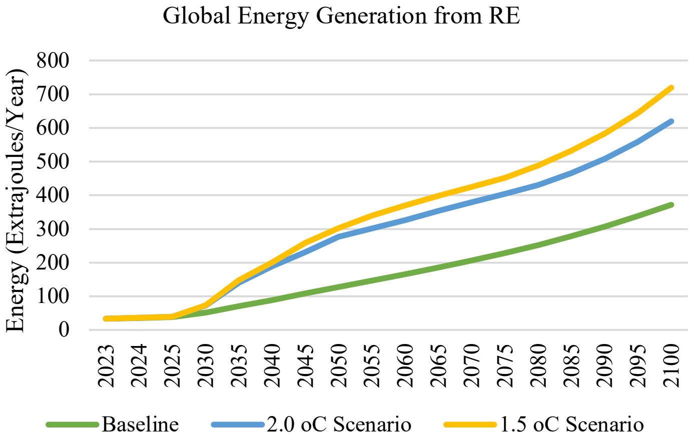
From additional findings, as summarized in Table 5.7 for the emission values at 2030, 2050, 2070, and 2100 across the four scenarios, the EOP, which is the only scenario with 100% RE possibilities, is not necessarily needed to keep the global temperature rising below 2°C by 2100. Working towards a total of about 77.3% RE in the global energy mix is enough to keep the global temperature, even at 2°C in support of the requirement for climate protection by the Paris Agreement. Similarly, at the same rate of 77.3 % RE, the global Carbon emissions would be dampened to 48.09, 25.5, 19.73, and 24.82 Gtons $CO_2$ eq in 2030, 2050, 2070, and 2100, respectively. However, this comes with a very high cost of Carbon pricing while reducing the subsidies for coal, oil, natural gas, and bioenergy, as was specified in the scenario inputs of Table B2, Appendix.

### 5.3.5 *Implications of Policy Scenario*

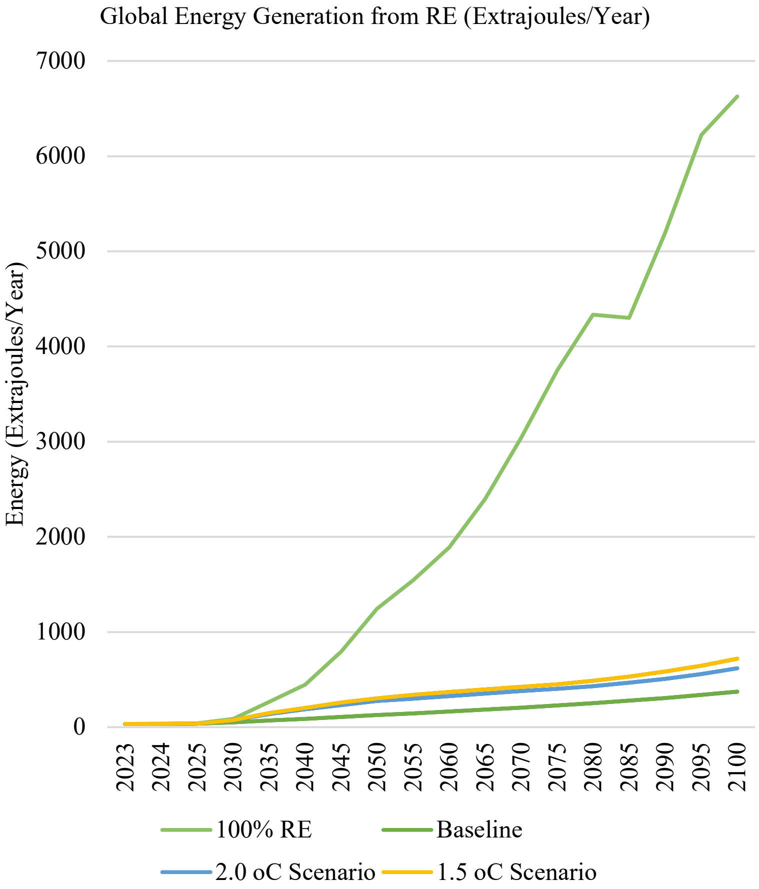
The choice of scenario has a significant impact on the global future energy mix, $CO_2$ emissions, and average global temperature levels. The BP scenario would lead to continued reliance on fossil fuels, high $CO_2$ emissions, and low energy costs. The OP scenario would result in a cleaner energy mix, lower $CO_2$ emissions, and higher energy costs. The MOP scenario would provide a balance between environmental and economic considerations, with medium $CO_2$ emissions, medium energy costs, and a focus on energy efficiency as the world faces a critical decision about its future energy mix.

The BP scenario is unsustainable in the long run, as it would lead to high $CO_2$ emissions and global temperature rise beyond 2.0ºC. The OP and MOP scenarios are more aligned with the IPCC climate commitment recommendations. However, it would require significant investment in the renewable energy infrastructure of power generation to account for about 77.3% and 82.82% of global primary production from RE, as in the OP and MOP scenarios, respectively. The EOP scenario offers the best ground as it is in line with the 100% renewable energy vision for all purposes, but it would require a very strong commitment beyond just new renewable energy infrastructure. In addition, even though bioenergy is not categorized as renewable due to the release of some emissions, tax/subsidy on bioenergy had the least impact on the global temperature levels compared with fossil fuels. Hence, bioenergy may still be needed in the energy mix as its advantages and environmental friendliness compared to fossil fuel cannot be overemphasized. These options need to be carefully considered in developing a comprehensive energy policy that balances all or most of the major approaches, strategies, and considerations made in the simulation.

Figure 5.11 (a) and (b) show the energy production requirement in extra joules that would be required for each scenario.



(a)



(b)

**Figure 5.11.** Global energy generation from RE.

Based on the results, a huge difference is seen in the extra joules needed for the 100% RE scenario, capable of keeping the global temperature levels at 1.1 ºC. For instance, about 6,627 extra joules are needed in the 100% RE scenario, compared with the 719 and 619, extrajoules for the 2.0, 1.5°C scenarios. Such a possibility would require unprecedented supporting actions to support such to happen, as well as dedicated efforts to achieve a high share of energy storage in the primary energy mix. Interestingly, these large extra joules can be drastically reduced if research breakthroughs result in a very high reduction of electricity requirement for energy storage production, such as hydrogen.

### *5.3.6 Limitation of the Simulation with EN-ROADS*

The limitations of this simulation with the EN-ROADS include:

1. EN-ROADS does not prioritize different renewable energy sources, focusing solely on reducing carbon emissions. It does not consider the possible benefits of diversifying into energy sources, such as enhanced geothermal and tidal energy, to minimize emissions

and improve storage. The technology assessment is limited as it does not consider the potential of individual renewable energies like geothermal and tidal energy, which can achieve a larger reduction in $CO_2$ emissions compared to bioenergy.

2. The simulation's annual resolution limits forecast that could help in responsive policy planning for efficient utilization of energy resources and daily operations of energy systems and infrastructures. The availability of data on an hourly basis would facilitate enhanced strategic planning for hosting capacity and the durability of infrastructure.

3. Economic Disparities: The study does not include an evaluation of the risks associated with investments and their attractiveness, which hampers the capacity to evaluate and rank viable solutions or most sustainable policy options.

The constraints found need the implementation of a more comprehensive methodology for the analysis of 100% renewable energy. The next sections present methodologies and assessment methods to overcome these constraints and provide a more comprehensive framework for analyzing upcoming energy situations. Therefore, the next sections bring together different procedures and evaluation approaches towards a common, comprehensive methodology for 100% RE analysis.

## 5.4 Towards a Common Procedure and Methodology for 100% Renewable Energies Analysis

The procedures of 100% renewable energy studies, as shown in Figure 5.12, are often determined by general rules for RE modelling and integration into the existing national energy grid to determine what best time and energy resource mix a country needs to attain a complete transition into clean energy. More recently, achieving 100% RE at low cost is now some of the ongoing research. However, from Table 5.1 and the succeeding discussion made earlier, the existing 100% RE studies tend not to have absolute consideration in energy policy and discussions, even with the most updated ones from national policies in [57] and guiding international energy plan and roadmap documents such as in [44], [66], [107], [117], [390]. Therefore, if the 100% RE concept is to gain complete trust in political discourse and national energy policy bills, more encompassing methods and typical approaches should be used to present results that reflect the current realities of countries and the limits to Earth’s natural resources. Possibly engaging in this endeavour would address the myths about the unrealistic assertion of achieving 100% RE globally. To evaluate such possibilities, different indices, methods, and determination procedures that consider all the aspects of sustainability are presented in this chapter, which can be useful for further investigating the feasibility of 100% RE integration within the 2030 – 2100 timeframe. By presenting these approaches already used in existing studies of 100% RE and including other considerations that further 100% RE should include in its analysis, this chapter envisages that the discussion presented herein can serve as the generally accepted methodology for use in comprehensive 100% RE analysis.

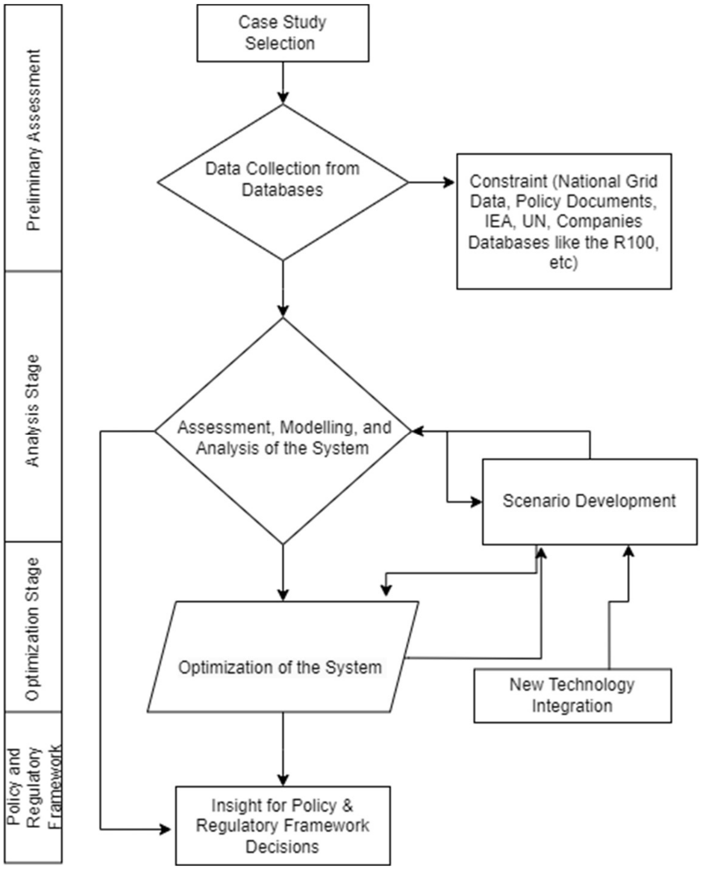


**Figure 5.12.** A simplified general rule for RE integration study and analysis. Source: authors' elaboration**.**

Several of the most beneficial design and modelling considerations in 100% RE evaluation would mainly include those stated in Table 5.8, as discussed subsequently in Section 5.3. By pursuing these metrics and incorporating the insights shared into 100% RE analysis, decision-makers, stakeholders, and policymakers can be properly informed about the technical, economic, social, and environmental aspects of achieving a 100% renewable energy future, thereby supporting the formulation of effective strategies and policies for a sustainable energy transition.

As a summary, Table 5.8 presents the key evaluation metrics that should be contained in a comprehensive 100% RE study, as previously discussed in detail.

**Table 5.8.** Key evaluation metrics in a comprehensive 100% RE studies. Source: authors' elaboration.

| 100% RE Evaluation Metrics | Indices |
|---|---|
| ESA | • Function<br>• Methodologies and mathematical approaches<br>• Time horizon<br>• Coverage<br>• Data requirements<br>• Logical assumptions |
| RRA | • Preliminary assessment<br>• Validation<br>• Observation |
| TIESR | • Regulating reactive power and voltage<br>• Frequency and dynamic power control<br>• Power quality problems<br>• Flow control in traffic<br>• Grid congestion |
| ROR | • General adequacy analysis<br>• Hosting capacity enhancement |
| EEI | • Energy return on investment (EROI)<br>• Levelized costs of energy (LCOE)<br>• Levelized costs of energy storage (LCOES)<br>• Life cycle assessment (emissions factors and damage impacts)<br>• Social life cycle assessment |
| PRA | • Green certificate system<br>• Feed-in-tariff<br>• Pure tendering process<br>• Energy subsidy<br>• Energy financing, carbon budgeting, and taxing<br>• Energy–environment–economy and development nexus |

The modelling process involves assessing the current energy infrastructure, including generation, transmission, and distribution systems, as well as simulating various scenarios based on the presented indices of Table 5.8 to determine the most effective strategies and technologies for achieving the transition to 100% renewable energy, as depicted in Figure 5.13 below.

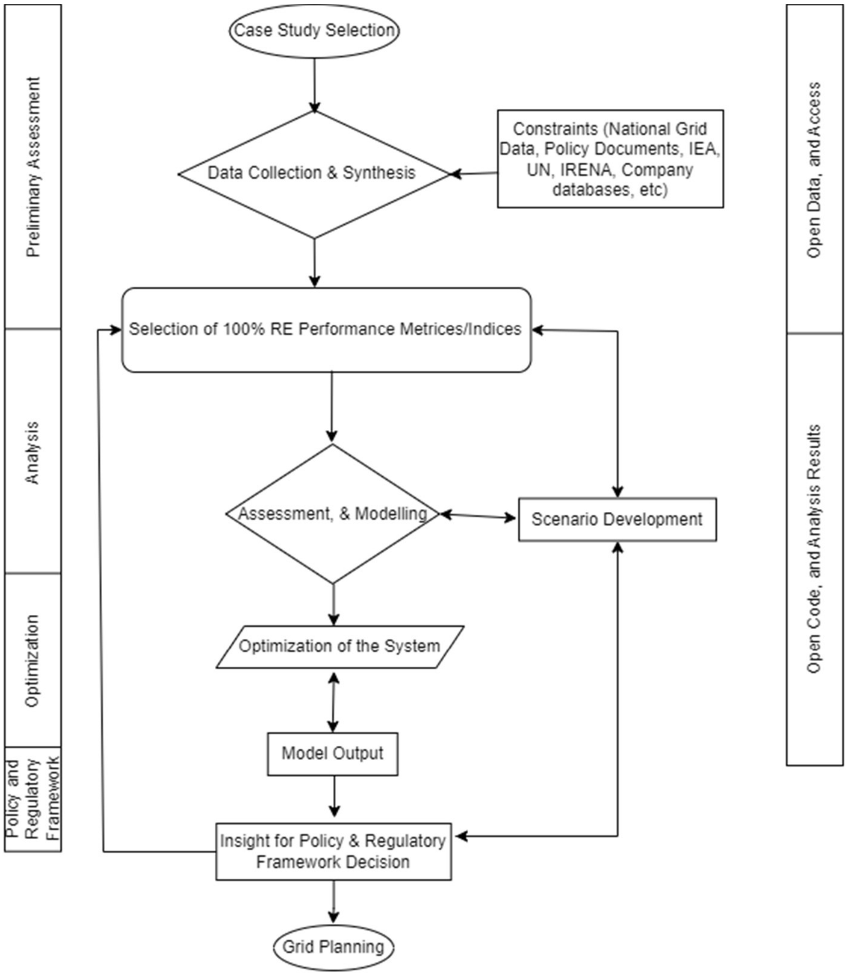


**Figure 5.13.** Ideal energy system modelling process for 100% RE. Source: authors' elaboration**.**

Moreover, different modelling processes for achieving the objectives of 100% RE analysis by decision-makers involve a variety of approaches, considerations, and tools/software to reduce both the amount of computation necessary and the accompanying costs of non-pragmatic assumptions. Some of these tools used in analysing systems towards 100% RE are compared in section 5.4, being highlighted and discussed in subsequent sections.

### *5.4.1 Preliminary Stage and Assessment*

The primary goal of 100% renewable energy studies should be to develop comprehensive and accurate models that simulate and analyse the feasibility, potential, and impacts of transitioning to a fully renewable energy system by presenting an optimal mix of factors and indices in the deployment of renewable energy sources, such as solar, wind, hydro, geothermal, and biomass, to meet the energy demands of a given region/country or system while eliminating reliance on non-renewable sources.

The preliminary stage would include three steps: identifying a case location for the study, extracting data from relevant resources and databases, and defining the sub-objectives for the study based on the following six evaluation metrics:

1. Energy system analysis.
2. Renewable resource assessment (RRA).
3. New technology integration with energy storage requirement (TIESR).
4. Economic, environmental, and social impacts (EEI) for sustainability.
5. Reliability, optimisation, and resilience (ROR).
6. Policy and regulatory analysis (PRA).

Therefore, these metrics are discussed in the next Sections 5.3.2–5.3.4.

### *5.4.2 Analysis Stage*

The analysis stage involves ESA, RRA, TIESR, and EEI.

a. Energy System Analysis (ESA)

It involves modelling the current energy system, including electricity generation and other sectors within the energy supply chain, such as transportation, construction/building sectors, to understand the existing infrastructure, energy demand, and associated greenhouse gas emissions; forecasting energy demand patterns and trends, considering factors such as population growth, economic development, energy efficiency measures, and electrification of various sectors; and determining the optimal mix of renewable energy sources and their spatial distribution to ensure reliable and cost-effective electricity generation while considering resource availability, land use, and environmental impacts.

According to the findings in [192], [391], [392], there are a variety of strategies that are employed by ESA for use in strategic, tactical, and operational decision-making at every time scale, from short, mid to long term[185], [346], [393], [394], [395], [396], [397], [398], [399], [400], [401], [402]. Since good decision-making must encompass the different concerns within the dimensions of sustainability (i.e., social, economic, and environmental difficulties), such as depleting fossil fuels reserves, greenhouse gas emission reduction, resource supply and price changes, and global warming, energy systems require adaptation and evolution. In addressing these concerns, energy systems are subjected to different forms of analysis using the modelling tools discussed in Section 5. Generally, these forms of analysis are expected to cover the following: general or specific functions, applicable methodologies and mathematical approaches, time horizons, sectoral or geographical coverages, data requirements, and logical assumptions of external/internal dependencies.

In Table 5.9, the description and the highlights of these forms of energy system analysis are presented.

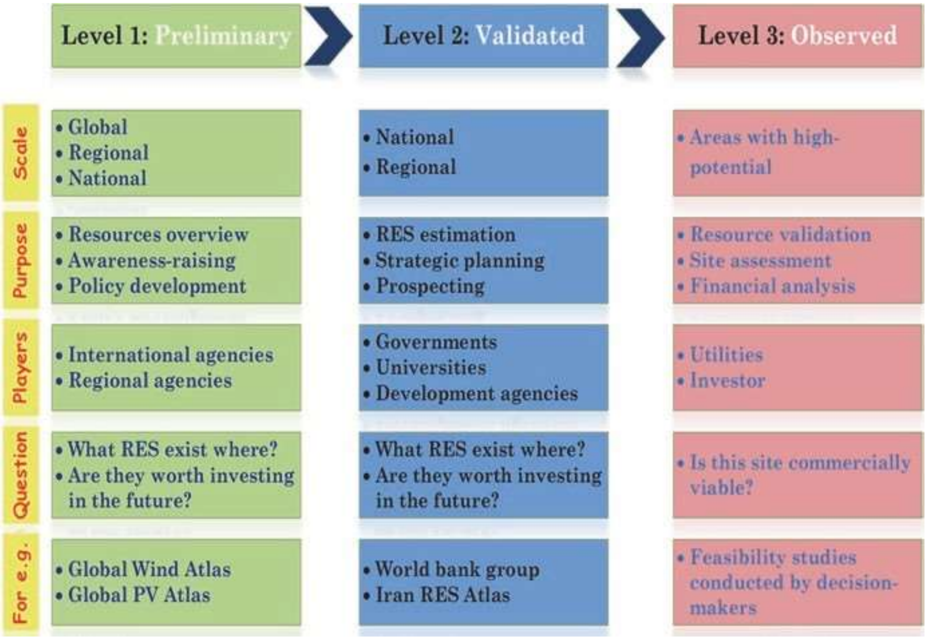
**Table 5.9.** Forms of ESA. Source: authors' elaboration.

| Form of ESA | Highlights | Refs. |
|---|---|---|
| Function | General (general future prediction and exploration)<br>Specific (prediction of energy demand, supply, consumption, pricing, GHG emissions, impact, appraisals) | [66], [101], [154], [322], [403], [404], [405], [406], [407] |
| Methodologies and mathematical approaches | Top-down (input-output models such as decomposition analysis, computable generic equilibrium model, system dynamics, and econometric models)<br>Bottom-up techniques (optimisation models, partial equilibrium model, simulation, and multi-agent models)<br>Mixed techniques<br>Degree of complexity<br>Model flexibility<br>Mathematical approaches (linear programming, dynamic programming, metaheuristic, and combination techniques)<br>Level of indices aggregation | [185], [186], [322], [325], [378], [399], [408], [409], [410], [411], [412], [413], [414], [415], [416], [417], [418], [419], [420], [421] |
| Time horizon | Short, mid, and long term | [375], [376], [422], [423], [424], [425], [426], [427] |
| Coverage | National/regional<br>Global<br>Local<br>Island<br>General purpose<br>Energy trade route | [394], [423], [428], [429], [430], [431], [432], [433], [434] |
| Data requirements | Level of data intensiveness | [248], [435], [436], [437] |
| Logical assumptions | Scenario (business as usual—BAU, RES)<br>Backcasting (considering the viability of both BAU and RES options over time)<br>Internal (degree of endogenisation, non-energy but related sector, energy technologies and end use)<br>External (economic and population growth, energy demand and supply, price and income, tax, and financing system) | [325], [438], [439] |

For 100% RE studies, the purpose of the analysis should ensure that the predictions are within the global target year to go net-zero on GHG emissions. The methodologies must consider the multi-criterion nature for a sustainable transition [440].

b. Renewable Resource Assessment (RRA)

It involves an analysis of the region's availability and variability of renewable energy sources such as solar, wind, hydro, geothermal, and biomass. This involves assessing the potential for energy generation, considering factors such as resource availability, intermittency, and spatial distribution, the requirements for upgrading and expanding the electricity grid infrastructure to accommodate increased energy demand renewable energy generation, including analysing transmission and distribution capacities, grid stability, and grid-balancing mechanisms. Morteza Z. and Behnam M. in [441] state that the following RRA levels exist: preliminary, validation, and observation. These three levels of RRA are presented as shown in Figure 5.14 below.



| | Level 1: Preliminary | Level 2: Validated | Level 3: Observed |
|---|---|---|---|
| Scale | • Global<br>• Regional<br>• National | • National<br>• Regional | • Areas with high-potential |
| Purpose | • Resources overview<br>• Awareness-raising<br>• Policy development | • RES estimation<br>• Strategic planning<br>• Prospecting | • Resource validation<br>• Site assessment<br>• Financial analysis |
| Players | • International agencies<br>• Regional agencies | • Governments<br>• Universities<br>• Development agencies | • Utilities<br>• Investor |
| Question | • What RES exist where?<br>• Are they worth investing in the future? | • What RES exist where?<br>• Are they worth investing in the future? | • Is this site commercially viable? |
| For e.g. | • Global Wind Atlas<br>• Global PV Atlas | • World bank group<br>• Iran RES Atlas | • Feasibility studies conducted by decision-makers |

**Figure 5.14.** RRA levels [441].

*c.* New Technology Integration with Energy Storage Requirement (TIESR)

This evaluation approach involves evaluating various renewable energy technologies, as well as their efficiency, costs, and scalability, followed by modelling the integration of these technologies into the existing energy system and interdependence, transmission, and energy storage requirements, such as batteries, pumped hydro storage, or thermal storage, to address the intermittent nature of renewable energy sources and ensure a reliable electricity supply. The rising penetration of various REs has created numerous technological issues for power grids, which continue as system components switch from a consumption mode to a supply one. Dispatched resources also impact power systems, such as intermittent renewable energy. Electricity companies have been forced to quickly change grid design and operating techniques due to the rising rates of renewable energy source penetration in various places [442].

Some nations have established strict regulatory frameworks that consider the technological resources at the disposal of power system operators to control the escalating installation rates effectively. The technical integration of RES into electricity networks has been the topic of numerous regional and national studies. Power system designers must consider every aspect of integrating variable renewable energy sources, as how these plans are carried out is greatly influenced by the state of the energy markets and the expected amount of RES penetration [441]. In increasing RES into current electricity grid networks, the following five technical requirements are crucial [443], [444][445]:

1. Regulating reactive power and voltage: The allowed deviation from the nominal voltage after using renewable energy sources ranges between ±5 and ±10% at the point of common coupling (PCC).
2. Frequency and dynamic power control: When used with power grids, intermittent renewable energy sources (RES) can increase or decrease active power generation, affecting the power system's frequency. Regulations now permit frequency deviations from the nominal frequency of −5% to +3% when RES is installed.
3. Power quality problems: Analyzing harmonic orders that cause waveform distortion and transient oscillations is the fundamental challenge with power quality. The use of international standards for power quality analysis when integrating renewable energy sources (RES) is important. In addition, the time index plays a crucial role in power system planning and operation, with voltage and frequency stability crucial for power quality issues [446].
4. Flow control in traffic: There might be limitations on the power supply channel from the RES connection point to subscriber areas, or additional RES capacity at the PCC might not be feasible.
5. Grid congestion may result from installing increased renewable energy capacity in various locations. Potential weak spots in the electric power system should be considered during planning to manage overloads.

Operators of power systems are responsible for preserving supply and demand equilibrium in short- to medium-term time frames [446]. Generation and transmission capacity are the two main measures for determining whether the entire power system can satisfy its annual electrical demand. Stability in the electricity system depends on how these measurements are interpreted when dynamic resources such as renewable energy sources (RES) are used [447]. The TIESR objective is paramount for a sustainable 100% RE, as the inability to manage any possible power or system interruption results in not meeting the goal.

### *5.4.3 Impact Assessment Stage - Economic, Environmental, and Social Impacts (EEI) for Sustainability*

This evaluation approach involves assessing the economic feasibility and cost-effectiveness of transitioning to 100% renewable energy, including evaluating the environmental benefits of transitioning to renewable energy, such as reduced greenhouse gas emissions, improved air quality, and climate change mitigation. Also, the social implications, including job creation, energy access, and community engagement, are considered. Given the importance of sustainability in every project, the general concept of the objective of EEI should be expected to incorporate the indices presented in Table 5.10 below.

**Table 5.10.** Forms and indices of EEI. Source: authors' elaboration.

| Form of EEI | Highlights | Refs. |
|---|---|---|
| Economic Impact | 1. Energy Return on Investment (kWh) | [72] |
| | 2. Life Cycle Cost of Energy (USD/kW) | |
| | (a) LCOE with Intermittency Factor | |
| | (b) Levelised Cost of Energy (LCOE) (USD/kW) | |
| | (c) Value-adjusted Levelised Cost of Electricity (vLCOE) (USD/kW) | |
| | (d) System Levelised Cost of Electricity (sLCOE) (USD/kW) | |
| | (e) Levelised Avoided Cost of Energy (LaCE) (USD/kW) | |
| | (f) Net Benefit ($N_{BP}$) (USD/kW) | |
| | (g) Levelised Cost of Energy Storage (LCOES) (USD/kW) | |
| | (h) Net Levelised Cost of Energy Storage (nLCOES) (USD/kW) | |
| | (i) Levelised Full System Costs of Electricity (fsLCOE) (USD/kW) | |
| Environmental Impact | 1. Emissions Factor Assessment based on Carbon Footprints of RE | [72] |
| | (a) Emissions from material combustion needed for RE system construction (by calculation method) (tons $CO_2$) | |
| | (b) Emissions from material combustion during RE system construction (by direct measurement) (tons $CO_2$) | |
| | 2. Damage Impact Assessment | |
| | (a) Natural Resource Impacts | |
| | i. Water Resource Depletion | |
| | ii. Land Use (LU) | |
| | iii. Energy Use (ENU) | |
| | iv Mineral, Fossil and Renewables Resource Depletion (MFRD) | |
| | (b) Abiotic Ecosystem Impacts | |

| | | | |
|---|---|---|---|
| | i. | Climate Change (CC) | |
| | ii. | Ozone depletion (ODP) | |
| | iii. | Freshwater Eutrophication (FEP) | |
| | iv. | Marine Eutrophication (MEP) | |
| | v. | Photochemical Ozone Formation (POF) | |
| | (c) | Human Health and Ecotoxicity | |
| | i. | Human Toxicity, Cancer Effects (HTc) | |
| | ii. | Human Toxicity, Non-cancer Effects (HTnc) | |
| | iii. | Particulate Matter (PM) | |
| | iv. | Freshwater Ecotoxicity (FEC) | |
| | v. | Ionising Radiation Human Health Effect (IRHH) | |
| Social Impact | 1. | Public Acceptance/Trust and welfare of stakeholders | [222], [448] |
| | 2. | Managing energy wars and dependencies | |

### *5.4.4 Reliability, Optimisation, and Resilience Stage*

The reliability, optimisation, and resilience (ROR) stage of the 100% RE studies involves analysing the potential challenges and risks associated with a renewable energy system, including the impact of extreme weather events, cybersecurity, and developing contingency plans to maintain system reliability and resilience. Expanding the current energy system to achieve 100% renewable energy penetration while ensuring system reliability, grid stability, and cost-effectiveness becomes a key issue in grid planning. It may involve exploring different scenarios, identifying optimal technology portfolios, and designing energy storage solutions. Some ways to ascertain the ROR of the 100% RE pathway can be evaluated using grid planning approaches not limited to general adequacy analysis and hosting capacity enhancement considering the technical requirements of RES integration into the grid, as discussed subsequently. The general equation form for assessment with these two approaches is well explained in Supplementary Materials S2 and Table S3 of this thesis research output published in [72].

a. General Adequacy Analysis

Intermittency in renewable energy production, caused by weather conditions, time of day, and season, poses a significant challenge in transitioning to a sustainable and 100% RE system. This variability affects the reliability and stability of the grid, leading to disruptions and blackouts. While energy storage technologies, such as hydrogen and batteries, have presented a great breakthrough for mitigating this issue [310], [449], their cost and technological limitations impact and hinder full adoption as the guaranteed singular solution [364], [408].

Fossil fuel power plants function as supplementary energy sources when renewable generation is insufficient and no longer becomes an option in 100% RE. Therefore, grid flexibility through planning strategies such as demand response programs, smart grid technologies, and advanced forecasting methods is crucial for managing supply availability to meet demand, manage fluctuations, and maintain stability. V. Rai [450] identified integration, coordination, and regulatory resources as emerging needs in the power sector. So, enhancing integration and coordination among various sectors, such as supply and demand, gas and electric operators, and electricity programs with non-electric social programs, are instrumental for ensuring 100% RE resilience.

The capability of the RE system to transition into 100% and to sustainably deliver the energy system demand under various conditions and scenarios can be determined with the use of generation adequacy analysis [450], [451], [452], [453], [454], [455], employing different deterministic and probabilistic techniques such as probability density function; convolution functions; correlation/regression; Markov process; frequency and duration; radial, parallel, and meshed network; point estimate; Monte Carlo; and artificial neural network techniques [456], [457], [458], which support the reliability evaluation of RE generation technology integrated into the national grid.

#### b. Hosting Capacity Enhancement

Hosting capacity (HC) limits and enhancement strategies of resources on grid distribution networks have been discussed by El-Ela et al. and Suchithra et al. in [171] [172], respectively. This assessment is important as it must be considered when planning a long-term grid for 100% RE. It would be particularly important in countries where the continuous grid integration of newer RE capacity is targeted, given limited resource availability and capacity constraints. An integrated strategy supports the interchangeability and complementarity of storage and line investment. It quantitatively assesses the constraints in distribution networks and their correlation with investments at the transmission and distribution levels. It would help determine the right investment options while optimising the different costs.

### 5.4.5 Policy and Regulatory Analysis (PRA)

Evaluating policy mechanisms, market structures, and regulatory frameworks that can facilitate the transition to 100% renewable energy and modelling the impact of different policies, incentives, and subsidies on investment decisions, market dynamics, and consumer behaviour are important [51], [189], [192], [194], [232], [373], [459], [460], [461]. Therefore, this would help inform policymakers and stakeholders about the necessary policy, regulatory, and market mechanisms to support the transition to 100% renewable energy, including incentives, targets, and regulations promoting renewable energy deployment and investment. The 100% RE studies can benefit by applying the expertise and further development of these legislative acts by governments to support sustainable energy technology. These mechanisms include the green certificate system, feed-in-tariff, pure tendering process, energy subsidy, energy financing, carbon budgeting and taxing, and energy–environment–economy development nexus.

a. Green Certificate System

Long-term, cost-effective, sustainable energy technologies are difficult to create in this system, but with the vision scenario of 100% RE access, more revenues that could serve as investments can be allotted to increase the probability of reaching net-zero through clean energy targets. A green certificate system can compensate for the gap between green electricity pricing and market prices. Certificates issued at the national level show how much renewable contribution comes from independent electricity generators and are placed as a measure by the government to encourage RE. Fines can then be charged through certificates with a less value RE contribution and put as budgetary allocation towards increasing the availability of renewable technologies. In their analysis, 100% of RE studies can also consider this mechanism by exploring the reasonable green certificate charges for a selected case study and the consequences on the clean energy target.

b. Feed-In-Tariff

The feed-in tariff is a mechanism set for a specific period, where suppliers are paid as profit for the full retail price per kilowatt-hour by electricity businesses by selling their output at market rates and receiving a set subsidy per kilowatt-hour [156]. Therefore, this would allow for intermediate and long-term technologies while encouraging high investments into 100% RE projects. However, harmonising them within the context of a country may be challenging. Overcompensation may occur if the tariff remains even if the cost of producing power decreases due to learning effects. Renewable energy storages targeted at supporting 100% RE actualisation can also receive a premium through a fixed-premium mechanism, a feed-in-tariff scheme.

c. Pure Tendering Processes

The government submits numerous bids for green electricity supply, with the price set by contract. Compensation is paid based on the going market rate for electricity. Tendering systems, while theoretically utilising market dynamics, can be unpredictable and challenging to plan for, and accepting low bids increases the risk of project completion. In these cases, the contract price set for projects aimed at 100% RE should consider the supply chain risks towards meeting the targets while considering the market dynamics and ensuring that uncertainties are managed properly.

d. Energy Subsidy (Renewables over Fossils)

Subsidies can largely shape the energy environment and affect the competitiveness of renewable fuel options. These subsidies help worldwide efforts to meet international climate goals, improve energy security, reduce fossil fuel imports, and progress technology. Renewable energy subsidies boost investment and innovation in the sector, creating jobs, public health benefits, and energy cost parity. They also equalise economic conditions, making renewables cost-competitive with fossil fuels. Renewable energy technology advances aid regional growth, power accessibility, and economic advancement. However, budgetary effects, political will, market distortions, and long-term viability are issues with renewable energy subsidies. Political will determines subsidy program fate and financial resource allocation. Subsidies can distort markets and consumer behaviour. The 100% RE analysis can also prove the appropriate route for policymakers to create well-targeted subsidy programs to maximise renewable energy subsidies' benefits and minimise their downsides.

e. Clean Energy Financing and Carbon Budgeting

Under the UN Kyoto Protocol in [80], the Clean Energy Mechanism (CDM) was the major criterion for financing clean energy projects in the form of assigned Certified Emission Reduction (CER) units, as entities whose strategies and visions contribute more to sustainable energy development projects tend to receive more supports [462]. The CER units are bought by industrialised nations (who are eventually signatories to the Kyoto Protocol) from the CDM emissions reduction projects in developing countries, posing a challenge to those who were not signatories but with very high GHG emissions, for instance, the USA and China. It resulted in the value of CER crashing significantly, thereby reducing the financial contribution to clean energy projects as many countries tried to recover from the devaluation of their non-remitted finances from old CERs, which is believed to be one of the major reasons for the failure of the COP25 [78][463]. Most importantly, this strategy has not been able to significantly reduce global GHG emissions as setting a cap on emissions and allocating that cap among countries, industries, or other entities are important and have been the most recent strategies of global carbon budgeting managed by the UNFCC under the National Determined Contribution initiative.

Because of other pertinent factors clean energy finance should consider, given the present push for climate justice, an all-inclusive system with the potential to consider relative benefit, compatibility, complexity, observability, trialability, and risk in energy financing and technology transfer protocols is important. A study by T. Ehlers in [464] used an index known as the S&P 500 Carbon Efficient Index, a quantitative method for evaluating the effectiveness of an organisation's carbon footprint and compared the enterprise's annual revenue with its emissions (i.e., the ratio of $CO_2$ emissions to annual revenue). Applying such an index in energy financing decisions alongside other development metrics towards countries with less economic and social power can be very useful, as this index's distinguishing feature is not just its encouragement of businesses to adopt more environmentally friendly practices but a climate justice system that seeks to place everyone in an advantaged position to attain the objective of low-carbon economic transition and the 100% RE.

f. Energy–Economy–Environment and Development (EEED) Nexus

Transitioning to 100% renewable energy sources is a key component of the present-day energy–-economy–environment and development nexus, which describes the intricate relationship between energy production, economic growth, environmental sustainability, and development. This idea acknowledges the interdependence of these factors and stresses the importance of a holistic approach to ensuring a sustainable and successful clean energy future. Part of the nexus is finding solutions to problems and balancing competing priorities. To be able to do the EEED evaluation towards 100% RE, an integrated assessment method that incorporates the previously discussed methods is essential to comprehensively assess both their technical, technological, and societal implications of pathways.

## 5.5 Towards a Common Modelling Tool for 100% Renewable Energies Analysis

### *5.5.1 Comparison of Related Energy Modelling Tools*

Several energy modelling tools exist and have been studied in previous works, such as comparative studies and review works in [368], [394], [432], [465], [466], [467], [468]. In line with the listing in [469], with a detailed description of most of the energy modelling tools, and the work by Khalili S and Breyer C. [304] that identified the energy modelling tools often used for 100% RE studies, a summary of the general modelling tools is presented in Table 5.11. A further addition is made to the list to include other software not identified by the other works and placed within the seven categories of the tool's usage at local or individual, island, national, global, all-purpose, 100% RE studies, and transition. Here, transition refers to the tool's capability to incorporate pathway modification or adjustment in the methods [470], [471], such as the metrics presented in this chapter needed by a country or selected case study to reach 100% RE. Table 5.12 matches the evaluation metrics in this chapter, with which existing 100% RE modelling tools have been used.

**Table 5.11.** General modelling tools and classifications with ones identified as mostly used for 100% RE studies. Source: author's elaboration.

| Tools | All Purpose | Local or Individual | Island | National | Global | 100% RE | (Transition) |
|---|---|---|---|---|---|---|---|
| MEDEAS | - | - | - | ✓ | ✓ | ✓ | ✓ |
| MESSAGE | - | - | - | - | ✓ | - | - |
| MiniCAM | - | - | - | - | ✓ | - | - |
| RAMSES | - | - | - | - | ✓ | - | - |
| WILMAR Planning | - | - | - | - | ✓ | - | - |
| PowerFactory DigiSILENT | - | ✓ | - | - | - | - | - |
| PERSEUS | - | - | - | - | ✓ | - | - |
| EMPS | - | - | - | - | ✓ | - | - |
| BALMOREL | - | - | - | - | ✓ | - | |
| LUT ESTM | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| WASP | - | - | - | ✓ | - | - | - |
| UniSyD3.0 | - | - | - | ✓ | - | - | - |
| 4see | - | - | - | ✓ | - | - | - |
| SIVAEL | - | - | - | ✓ | - | - | - |
| SimREN | - | - | - | ✓ | - | - | - |
| ORCED | - | - | - | ✓ | - | - | - |
| INFORSE | - | - | - | ✓ | - | - | - |
| ProdRisk | - | - | - | ✓ | - | - | - |
| STREAM | - | - | - | ✓ | - | - | - |
| AEOLIUS | - | - | - | ✓ | - | - | - |
| E4Cast | - | - | - | ✓ | - | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| IKARUS | - | - | - | ✓ | - | - | - |
| EnergyPLAN | - | - | - | ✓ | - | ✓ | ✓ |
| PRIMES | - | - | - | ✓ | - | - | - |
| LEAP | - | - | - | ✓ | - | ✓ | - |
| GTMax | - | - | - | ✓ | - | - | - |
| MODEST | - | - | - | ✓ | - | - | - |
| Mesap PlaNet | - | - | - | ✓ | - | ✓ | ✓ |
| ENPEP-BALANCE | - | - | - | ✓ | - | - | - |
| EMCAS | - | - | - | ✓ | | - | - |
| NEMS | - | - | - | ✓ | | - | - |
| MARKAL/TIMES | - | - | - | ✓ | | - | - |
| Invert | - | - | - | ✓ | | - | - |
| EMINENT | - | - | - | ✓ | | - | - |
| H2RES | - | - | ✓ | - | - | - | - |
| HOMER | ✓ | - | - | - | - | ✓ | - |
| COMPOSE | ✓ | - | - | - | - | - | - |
| ETEM | ✓ | - | - | - | - | - | - |
| HYDROGEMS | ✓ | - | - | - | - | - | - |
| energyPRO | ✓ | - | - | - | - | - | - |
| BCHP Screening | ✓ | - | - | - | - | - | - |
| TRNSYS | ✓ | - | - | - | - | - | - |
| MODEST | ✓ | - | - | - | - | - | - |
| PVSys | ✓ | - | - | - | - | - | - |
| LOADMATCH | - | - | - | - | - | ✓ | ✓ |
| TIMES | - | - | - | - | - | ✓ | ✓ |
| REMix | - | - | - | - | - | ✓ | - |
| ISA Model | - | - | - | - | - | ✓ | - |
| PyPSA | - | - | - | - | - | ✓ | - |
| NEMO | - | - | - | - | - | ✓ | - |
| GENeSYS-MOD | - | - | - | - | - | ✓ | ✓ |
| VENSIM/C-ROAD/EN-ROAD | - | - | - | - | ✓ | ✓ | ✓ |
| AU Model | - | - | - | - | - | ✓ | ✓ |

The use of ✓ shows that the tool can be used for that purpose under the category.

**Table 5.12.** Key evaluation metrics with the identified tools for 100% RE studies. Source: author's elaboration**.**

| Tools | ESA | RRA | TIESR | ROR | EESI | PRA |
|---|---|---|---|---|---|---|
| MEDEAS | ✓ | ✓ | - | - | - | - |
| LUT ESTM | ✓ | ✓ | partially | - | partially | - |
| EnergyPLAN | ✓ | ✓ | - | - | partially | - |
| Mesap PlaNet | ✓ | ✓ | - | - | - | - |
| HOMER | ✓ | ✓ | - | - | - | - |
| LOADMATCH | ✓ | ✓ | - | - | - | - |
| TIMES | ✓ | ✓ | - | - | - | - |
| REMix | ✓ | ✓ | - | - | - | - |
| ISA Model | ✓ | ✓ | - | - | - | - |
| PyPSA | ✓ | ✓ | - | - | partially | - |
| NEMO | ✓ | ✓ | - | - | - | - |
| GENeSYS-MOD | ✓ | ✓ | - | - | - | - |
| VENSIM/C-ROAD/EN-ROAD | ✓ | partially | partially | partially | partially | ✓ |
| AU Model | ✓ | ✓ | - | - | - | - |

The use of ✓ shows that the tool can be used for that purpose under the category.

Generally, and from the comparison in Table 5.8 and 5.9, the two most used models for assessing 100% RE systems are EnergyPLAN and LUT-ESTM [304] because of their overall benefits when it has to do with their application to different industrial sectors, transition modelling (although EnergyPLAN is unable to perform this), optimisation, full hourly simulation, off-grid integration, and carbon capture strategies (CCS). The later benefits of CCS inclusion have been newly introduced in LUT-ESTM. For the description of the advantages and limitations of all the tools, several studies have been made already, such as those included in references [322], [394], [429], [430], [432], [465], [466], [469], [472], [473], [474], [475], [476]. However, not all tools are comprehensive enough to address all the limitations of each one, and most importantly, the challenges and needs of some countries, such as energy security through regional integration [477], varying technical capacities [297], energy trade [478], biophysical & socioeconomic constraints, and study objectives such as holistic integration of the different aspects of sustainability into the 100% RE analysis have been discussed in this study.

Further challenges raised by S. Khalili and C. Breyer in [304] and T. Remy et al. in [479] observed that not a single EST supports off-grid integration, which is of utmost significance for research on energy transitions in sub-Saharan Africa [480]. The energy transition into full renewables in developing countries such as those in Africa may have to take a different paradigm, as discussed by I. Aniebo et al. [116], in addition to the fact that not all the population is yet to have 100% electricity access, already highlighted in Section 5.2.3 of this work. Following the earlier mentioned limitations, it is worth noting that there is currently no energy system modelling tool of the functionalities of integrated assessment models (IAMs) in undertaking detailed analyses of 100% energy systems within the framework of long-term climate change constraints. This specific goal is a key area that needs concentration as IAMs tend to ignore studies on 100% RE systems.

There has been some recent progress, such as alternative integrated tools for long-range energy planning [412], modelling frameworks to integrate global socioeconomic and biophysical constraints [481], life cycle sustainability assessment for multi-renewable energy systems [482] and integrated tools for spatial representation of high-quality data of renewable energy technologies for expansion planning models [428]. A more representative example is the VENSIM/C-ROAD/EN-ROAD, which is a climate simulator created collaboratively by MIT Sloan Sustainability Initiative, Climate Interactive, and Ventana Systems (owners of VENSIM) that employs the principles of system dynamics and thinking [27]. This tool facilitates the analysis of the effects of policies such as electrification, carbon pricing, and agricultural practices on different factors, including energy prices, temperature, air quality, and sea level rise [27]. The C-ROADS Simulator aids in comprehending the effects of countries' emission reduction commitments in the United Nations and evaluating the long-term consequences of various climate strategies in different regions. C-ROADS allows for the efficient evaluation of policy effectiveness in achieving temperature stabilisation below 2°C and examining the various types of plans, encompassing differences in reduction rates and target years. However, the setback with the VENSIM/C-ROAD/EN-ROAD tool has been highlighted and presented in Tables 5.8 and 5.9, where they are mainly used for global policy and regulatory analysis (PRA) and energy system analysis (ESA) based on embedded data from international agencies. In contrast, the rest of the metrics can only be partially done by drawing insights into decisions from the results obtained from the other functionalities of the simulator.

### *5.5.2 Proposed Key Elements in Energy Modelling Tool for 100% RE Analysis*

Frameworks that require several forms of integrated system modelling can be best supported with the use of a dynamic approach and the evaluation metrics/indices proposed in this chapter, and this can be attempted given a thorough understanding of the problem statement and a clearer picture of what solution is desired, as well as developing a hypothesis and pathways that suit the problem statement and scenario definition. This method is dynamic and would require interdisciplinary discussion to ensure that proposed solutions or pathways are technically sound, pragmatic, and feasible. For this to happen, the use of an IAM requires not just an in-depth understanding of the problem or means to reach 100% RE, as in this case, but that the solutions are pre-determined with the right scenarios, and hypotheses backed up with the right data and or applicable modelling key elements and capabilities. Therefore, in Table 5.13, additional key elements are summarised and presented that should be included in a comprehensive EST in addition to existing capabilities for holistic 100% RE studies.

**Table 5.13.** Proposed key elements and modelling capabilities for energy modelling tools and integrated assessment for 100% RE studies. Source: author's elaboration.

| S/N | Key Elements | Capabilities | Ref |
|---|---|---|---|
| 1 | Data quality | High-quality data for geographical/spatial consideration<br>Representation of both low and high emissions countries<br>Data fairness | [428] |
| 2 | Planning | Long-term planning<br>Investment planning tool<br>Generation of policy and regulatory frameworks for the case study<br>Transition modelling with representative scenario assumptions | [412] |
| 3 | Integration | Carbon capture and storage modelling<br>Off-grid integration<br>Optimisation<br>Inclusion of both energy for electricity and non-electricity purposes | [481] |
| 4 | Tools Coupling and Transparency | Interoperability with existing EST<br>Public transparency of datasets and source codes<br>Compliance with standards | [438], [483] |
| 5 | 100% RE Evaluation Metrics | Energy system analysis (ESA)<br>Renewable resource assessment (RRA)<br>New technology integration with energy storage requirement (TIESR) Economic,<br>Environmental, and social impacts (EEI) for sustainability | This chapter |

## 5.6 Conclusion

The use of renewable energy technologies not only helps the economy, society, and the environment but also advances the cause of sustainable development, as discussed in preceding sections of this work, which has necessitated the need for a net-zero carbon society through the transition into full deployment of renewable energy for all use. The thesis explores the transition towards 100% renewable energy (RE) at the global level, focusing on the effects of temperature levels on the transition. It presents a discussion on the pathway possibilities and challenges of achieving 100% RE and its impact on climate scenarios. The study uses baseline, optimum, more optimum, and extreme optimum path scenarios and an integrated assessment model to analyze the implications of each action on factors like global temperature, GHG emissions, and energy storage breakthrough. The findings suggest that urgent efforts are needed to keep the global average temperature below $3.3^0$C, with the most optimistic scenario requiring 75.5-998% RE to keep temperature rise below 1.50C.

The ongoing shift towards 100% RE raises inquiries regarding the possibility and sustainability of such an endeavour on the global stage, even though some countries, as mentioned in Table 5.2, have already attained or are near this goal. Numerous research topics and discussions underscore the current deficiencies in the knowledge that necessitate attention to foster the emergence of viable prospects for development within the realm of the green economy. Considering the multi-faceted obstacles linked to engagement in the transition towards complete clean energy, it is crucial to formulate novel frameworks that can adequately investigate the expansion and advancement of clean energy endeavours. When formulating strategies to promote growth, it is imperative to consider various factors such as technical, socio-economic, environmental, and developmental constraints.

This study lays the foundation for future research on technical and non-technical approaches to promote a sustainable transition to a 100% RE by providing key elements, particularly the proposed 100% RE evaluation metrics, which include energy system analysis (ESA); renewable resource assessment (RRA); new technology integration with energy storage requirement (TIESR); economic, environmental, and social impacts (EEI) for sustainability; and policy and regulatory analysis (PRA). While these metrics with indices have been proposed and discussed in this study, future work should focus on demonstrating how these indices can aid in developing more holistic pathways for transition into 100% RE in countries, regions, and the world.

It is imperative to undertake additional research to comprehensively examine how these evaluation metrics have been employed in various countries. For instance, with the record from Table 5.4 showing that the studies carried out in several countries, particularly with high $CO_2$ global contributions, have only considered a few of the strategies and evaluation mechanisms shared in this study, an opportunity can be explored to investigate into ways that they can transition into complete RE using several other indices presented in this work. Additionally, there is hardly any single 100% RE study or integrated tool that performs a comprehensive evaluation of transitioning into 100% RE; this study has only been able to propose evaluation metrics without a case study modelling demonstration of the use of many or all metrics in methodologies for 100% RE analysis. Hence, there is a need for a robust yet transparent 100% RE analysis capable of using most or all the six evaluation mechanisms in presenting pragmatic results that win the trust of the public and government/private investment in full clean energy projects.

It necessitates using an inclusive method during such 100% RE analysis to demonstrate how important national and regional development issues and constraints should not be left out in the quest for full 100% RE utilisation for all purposes. This work also proposes the need for the establishment and refinement of existing integrated energy models reviewed in Sections 5 and 6 to specifically be designed to accommodate developmental versus decarbonisation transitional processes such as the ones mentioned by Tambari I. and Dioha M. in [208], which the narrative in this thesis believes would be instrumental towards a complete 100% RE and energy equity for all. These models would aid end users, utilities, and prosumers in the efficient planning and execution of sustainable energy and electricity generation, distribution, and usage across countries and cities, as these would significantly impact the development and implementation of national and international energy policies.

# Chapter 6

# Summary and Conclusion

**Akpan J.**, Oludolapo O., (2023)"Towards a simplified and integrated model for climate-energy resources & systems planning" *IEEE 4th IEEE UK&I YP Postgrad STEM Research Symposium,* Newcastle upon Tyne

## 6.1 Summary of Chapter 1

In the first chapter, the foundation for the thesis is made by discussing the context of the climate catastrophe, the diversity of energy resources and systems in tackling the climate crisis, the issues posed by energy diversity, and the solutions offered by integrated methods and IAM, as well as the utility and growth of systems thinking in IAMs. Following the thesis's problem statement, knowledge gaps are introduced, along with the narrative for research model formulation and justification for model design. The thesis begins with a presentation of the research question, followed by a discussion of the aims, the methods that would be employed, the relevance and value of the study, and finally, the thesis's organization and conclusion.

## 6.2 Summary of Chapter 2

Sustainable energy development (SED) is a crucial component of the Sustainable Development Goals (SDG), aiming to maintain economic and social progress while protecting the environment and mitigating climate change's effects. SED serves as a transition paradigm for sustainable development, providing a blueprint for energy, peace and prosperity for people and all uses. This chapter presents the history of SED and then uses a critical discourse approach to summarize existing review studies in SED. Ten interlinked themes of SED are identified, with two of them considered to be among the least studied in existing SED reviews and in the current global discussion around climate change. The chapter explores these two themes, which include energy financing and the need for 100% renewable energy (RE), a sub-theme of decarbonization strategy working towards the 1.5 – 2.0 °C scenario. The chapter suggests that the current G20 countries' contributions, if maintained continuously per annum, in addition to 80% more funding from private investment compared to the amount in the 1.5 °C scenario financial requirements for clean energy, are sufficient to limit global warming. In addition to the present drive for 100% RE, the article also discusses emerging issues, such as energy storage options with an indication of hydrogen as the most promising, other energy-related development agendas, and the need for regional security stability to prevent energy wars. Selected SED decarbonization strategies are presented across the power, transport, building, and industrial sectors. The chapter concludes with progress and directions for future research, mainly the need for re-defining nationally determined contribution (NDC) through an emissions budgeting and centralized global or regional emissions stock-taking strategy working towards the 1.5 °C scenario.

## 6.3 Summary of Chapter 3

Chapter 3 presents an analysis of the impact of Nationally Determined Contributions (NDC) under the Paris Agreement on global temperature rise. With the use of a climate simulation tool based on the concept of system dynamics, the study constructs a framework as an environment model to project global temperature changes under other policy scenarios. The hypothesis is formulated based on the analysis of current, announced, and best-case global/national policy scenarios. The research aims to address critical questions regarding the effectiveness of the ongoing NDC commitments in limiting global temperature rise to well below 2°C, in alignment with the Paris Agreement's goals. The simulation results offer a roadmap by presenting possible grey areas for optimising the current NDCs in global and national energy policies and treaties, fostering international collaboration, and reinforcing the global commitment to combating climate change. In addition, this study also presents other potential strategies for decarbonization associated with facilitating the implementation of just and fair NDCs.

## 6.4 Summary of Chapter 4

The technical feasibility of reaching 1.5°C climate goals is believed to be possible, but the challenge lies in meeting the financial requirements for this to happen. Because climate change has been identified as a danger to the financial system, yet has been least studied in literature, although presently gaining interest in research. Therefore, a conceptual framework to assess the financial viability of climate policies and possible effects on transition financing is necessary. Evaluating the financial viability of different policy scenarios of transition finance towards average global temperature levels can be useful in investment planning. Hence, Chapter 4 developed a simplified integrated emissions cost budgeting model based on capital budgeting techniques to determine the financial viability and attractiveness of different investment paths meant to attain key selected policy scenarios. The economic benefits of various funding needs and emission-reduction strategies for combating climate change are assessed using a cost-benefit analysis approach. The approach involves estimating and evaluating the monetary value of both avoided and unavoided emissions costs of implementing a specific policy and comparing them in terms of net present value to obtain the cost-benefit index. The model was developed using five global scenarios, which are the announced policies type 1, announced policies type 2, 2.0°C scenario, and the 1.5°C scenario. The potential values for Carbon mitigation and emission reduction on the average global temperature level in each of the five scenarios were investigated in Chapter 3. With the use of the model in Chapter 4, the economic attractiveness of each scenario is explained in this work using emissions data from the study in Chapter 3.

Furthermore, an illustrative application of the model was employed for the emissions value of China, the USA, India, and the European Union (EU).

The avoided emissions growth rate in five scenarios and three cases depreciates with increasing discount rates. The 1.5°C scenario results in the highest reduction of emissions, while the baseline scenario has a growth rate between 139.48% and 146.5%. It suggests that financial commitment is insufficient due to the 2.4 USD Trillion-unit emissions removal cost. The model validation validates the time value of each policy scenario using capital budgeting principles. Delays in policy implementation result in different net present values and cost-benefits, and the NPV and BI values on each policy option depreciate compared to starting the investment in the first planned year. This validation aligns with real-world cases where increasing GDP often leads to inflation and increased capital costs for projects. The model is aimed at promoting the narrative of the net present value and time value of policies for emissions mitigation and to demonstrate the attractiveness of clean energy and climate investments to protect society from the consequences of climate change because of global temperature rise. Future recommendations for the applicability of the simplified model include the possibility of being linked to existing integrated assessment tools as, to the best of my knowledge, none have the features of cost-benefit analysis of climate scenarios. Also, the model can be used to assess the economic attractiveness of emissions mitigation policies in other countries, cities, and organizations. Hence, the model and methodological approach developed in this Chapter show a promising usefulness of its applicability.

## 6.5 Summary of Chapter 5

The accelerated population growth and increased energy consumption in developed nations have a significant impact on the worldwide emissions of carbon dioxide. While it is true that wealthy nations have successfully attained universal access to electricity, a significant number of developing countries continue to face challenges in this regard. The circumstances, as mentioned earlier, provide both obstacles and prospects in the pursuit of the United Nations' Sustainable Development Goals (SDGs) 7 and 13. Renewable energies have been acknowledged as a substantial advancement in this undertaking, as evidenced by the fact that 30 nations have already achieved a renewable energy share of over 70% in their national power mix.

The chapter examines the global transition towards 100% renewable energy (RE) and its impact on global temperature levels. It discusses the possibilities and challenges of achieving 100% RE and its impact on climate scenarios. The study uses baseline, optimum, more optimum, and extreme optimum path scenarios and an integrated assessment model to analyze the implications on global temperature, GHG emissions, and energy storage breakthroughs. The findings suggest that for 100% RE to be possible, energy production from RE may require the production of at least 6000 extra joules per year and can keep the global average temperature well below 2.0°C, even at 1.1°C. This Chapter also presents a comprehensive examination of six evaluation metrics needed for a unified assessment approach in 100% renewable energy systems analysis.

Additionally, it critically examines several energy modelling tools to determine their suitability for conducting such analyses. The objective of this assessment is to establish a unified and comprehensive approach, along with a modelling tool, for evaluating the complete implementation of renewable energy sources in nations that achieve optimal trade-offs. It would assist in the effective planning of national and regional energy resources and systems for upcoming energy initiatives, hence promoting sustainable development.

## 6.6 Final Remarks

Consequently, considering these dynamics of cross-sectoral interactions and the interrelation between the SED themes as highlighted in this thesis, there is a need to explore timely strategies towards the 1.5°C Scenario and SDGs' vision. In the current energy paradigm, SED themes involving emerging issues like energy storage and developmental indices such as energy accessibility, affordability, independency issues, and energy-X (where X can be other infrastructures or areas such as food, water, and land) nexus continue to be instrumental towards developing a comprehensive, integrated assessment approach to evaluate and manage multiple energy potentials, resources, and systems while creating a link between energy systems or policies and sustainable development goal 7 (clean and affordable energy for all), goal 13 (climate change action), and other relevant goals of the SDGs towards the 2030 United Nations' targets.

Given the urgency of the climate problem, an all-encompassing strategy for the energy transition is needed, one that considers the least-carbon aspects, economic viability, and environmental emissions commitment. It entails implementing time-valued emissions rules, new policies for reducing emissions, and sustainable, fair, and just energy practices. Governments, businesses, and communities must work together to ensure that everyone has fair access to clean energy and that sustainable practices meet that demand. Increasing the diversity of energy systems and resources is crucial to addressing climate disasters. This thesis used Systems Dynamics Modelling (SDM) and Integrated Assessment (IAM) that integrates technical, social, and technological trends with environmental repercussions when addressing complex situations. IAMs concentrate on how changes in land use policy, dietary modifications, fertilizer use, farming practices, and afforestation affect GHG emissions. Incorporating diverse perspectives, analyzing trade-offs between environmental sustainability and economic growth, simulating complex interactions, identifying unintended consequences, facilitating policy evaluation, evaluating the social, economic, and environmental impacts of various mitigation options, and facilitating stakeholder engagement are just a few of the many advantages that SDM models offer for addressing complex challenges.

Energy makes up almost 70% of all greenhouse gas emissions, making it an essential component of modern living situations. Nonetheless, 80% of primary energy still comes from fossil fuels. The physical constraints on both renewable and non-renewable energy sources must be considered while addressing climate change, as well as important regions for energy development. The research has utilized systems dynamics modelling to simulate a just and equitable emissions reduction program that would raise world temperatures by an average of 1.5°C. The intricate relationships between human activity, the environment, energy, and the economy can also be studied using integrated models. In order to meet the targets of the climate scenarios, the research questions address the long-term effects of various mitigation and adaptation strategies for climate change, offer transitional pathways to the optimal climate scenarios, and develop an economic model to assess the costs, benefits, and risks associated with various environmental policies. The results of these models are helpful in planning energy systems and resources for sustainable practices so that climatic scenarios stay under the 1.5 to 2.0°C temperature increase limitations set by the IPCC.

# Appendices

## Appendix A1 (Environment Model)

### Definition of Hypothesis for the Environmental Model of Chapter 3

**Table A1.** Hypothesis Definition for each of the Scenarios

| Peak of Emissions (Year) | Start of Emissions Reduction (Year) | Emissions Reduction Rate (% per annum) | Countries |
|---|---|---|---|
| | | Scenario- Baseline | |
| 2100 | 2100 | 0 | China |
| 2100 | 2100 | 0 | US |
| 2100 | 2100 | 0 | India |
| 2100 | 2100 | 0 | EU |
| 2100 | 2100 | 0 | The rest of the Advanced Countries |
| 2100 | 2100 | 0 | Rest of the Developing Countries |
| | | | |
| | | Announced Policies Type 1 | |
| 2023 | 2023 | 0.94 | China |
| 2023 | 2023 | 0.928 | US |
| 2023 | 2023 | 0.915 | India |
| 2023 | 2023 | 0.903 | EU |
| 2100 | 2100 | 0 | The rest of the Advanced Countries |
| 2100 | 2100 | 0 | Rest of the Developing Countries |
| | | Announced Policies Type 2 | |
| 2023 | 2023 | 0.94 | China |
| 2023 | 2023 | 0.928 | US |
| 2023 | 2023 | 0.915 | India |
| 2023 | 2023 | 0.903 | EU |
| 2023 | 2023 | 0.9 | The rest of the Advanced Countries |
| 2023 | 2023 | 0.9 | Rest of the Developing Countries |
| 2023 | 2023 | 0.94 | China |
| | | 2.0ºC Scenario | |
| 2023 | 2023 | 2.5 | China |
| 2023 | 2023 | 2.5 | US |

| | | | |
|---|---|---|---|
| 2023 | 2023 | 2.5 | India |
| 2023 | 2023 | 2.5 | EU |
| 2023 | 2023 | 2.5 | The rest of the Advanced Countries |
| 2023 | 2023 | 2.5 | Rest of the Developing Countries |
| | | 1.5°C Scenario | |
| 2023 | 2023 | 6 | China |
| 2023 | 2023 | 6 | US |
| 2023 | 2023 | 6 | India |
| 2023 | 2023 | 6 | EU |
| 2023 | 2023 | 6 | The rest of the Advanced Countries |
| 2023 | 2023 | 6 | Rest of the Developing Countries |

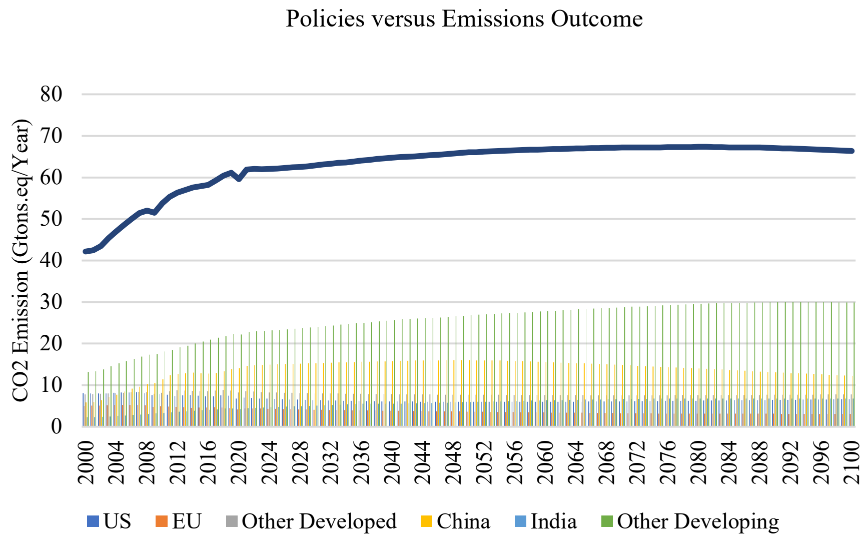


**Figure A1**. Global $CO_2$ Emissions with Baseline Path

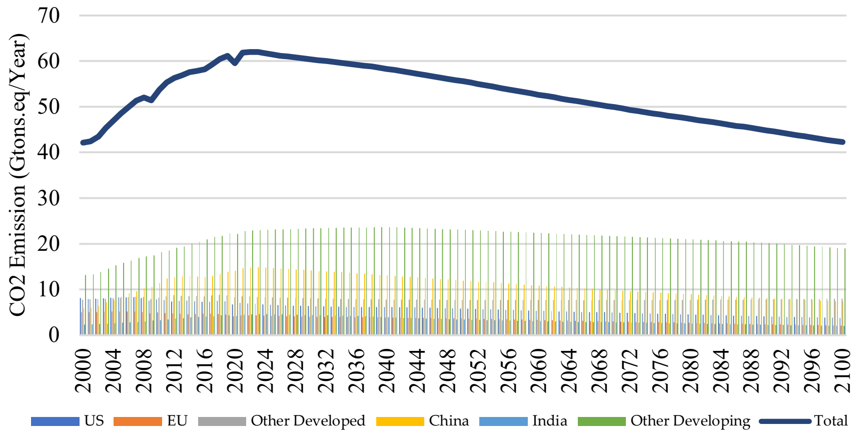


**Figure A2.** Global $CO_2$ Emissions with Announced Policies Type I

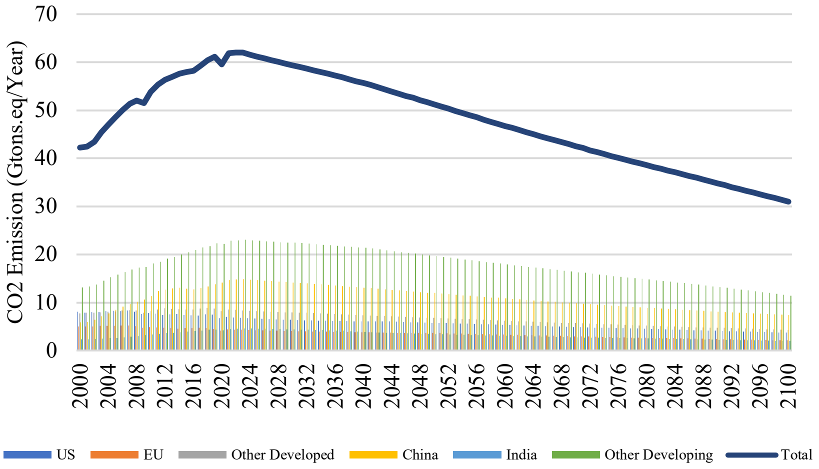


**Figure A3**. Global CO$_2$ Emissions with Announced NDC Policies Type 2

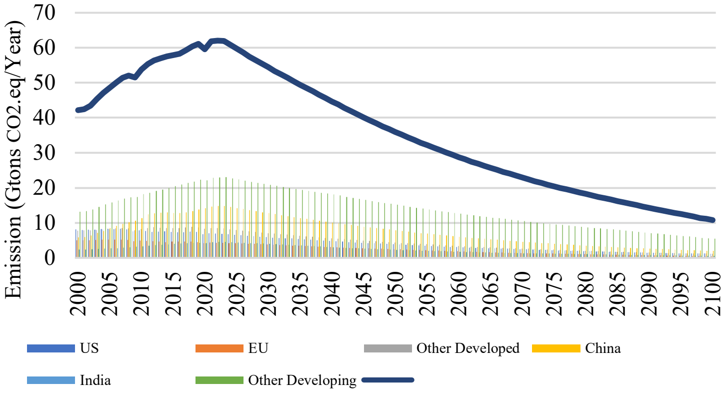


**Figure A4.** Global CO$_2$ Emissions with 2.0ºC Scenario

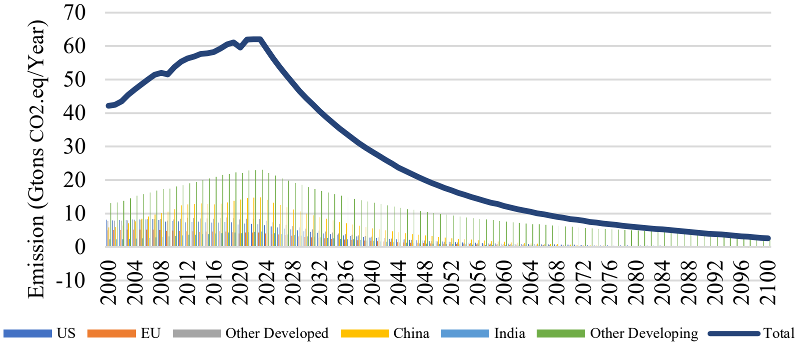


**Figure A5.** Global CO$_2$ Emissions with 1.5ºC Scenario

# Appendix A2 (Economic Model)

Emissions per policy, unavoided emissions cost, and avoided emissions cost, respectively. The full dataset is available in the supplementary material of our research output in [228].

**Table A2.** Global Policies and Emissions (Gtons $CO_2$.eq/Year) through Simulated Period

| Years | Baseline Case | Announced Policies Type 1 | Announced Policies Type 2 | 2.0 °C Scenario | 1.5 °C Scenario |
|---|---|---|---|---|---|
| 2023 | 61.98 | 61.98 | 61.98 | 61.98 | 61.98 |
| 2024 | 62.03 | 61.71 | 61.56 | 60.83 | 59.04 |
| 2025 | 62.13 | 61.47 | 61.17 | 59.7 | 56.26 |
| 2026 | 62.24 | 61.22 | 60.77 | 58.59 | 53.62 |
| 2027 | 62.39 | 61.02 | 60.4 | 57.52 | 51.14 |
| 2028 | 62.53 | 60.81 | 60.05 | 56.47 | 48.8 |
| 2029 | 62.71 | 60.62 | 59.68 | 55.42 | 46.59 |
| 2030 | 62.9 | 60.42 | 59.36 | 54.4 | 44.48 |
| 2031 | 63.09 | 60.24 | 59.02 | 53.4 | 42.5 |
| 2032 | 63.27 | 60.04 | 58.65 | 52.39 | 40.61 |
| 2033 | 63.46 | 59.82 | 58.27 | 51.39 | 38.8 |
| 2034 | 63.65 | 59.63 | 57.93 | 50.41 | 37.1 |
| 2035 | 63.83 | 59.43 | 57.58 | 49.44 | 35.48 |
| 2036 | 64.05 | 59.23 | 57.21 | 48.49 | 33.96 |
| 2037 | 64.23 | 59.04 | 56.86 | 47.56 | 32.5 |
| 2038 | 64.4 | 58.81 | 56.44 | 46.58 | 31.06 |
| 2039 | 64.55 | 58.56 | 56.03 | 45.63 | 29.7 |
| 2040 | 64.73 | 58.33 | 55.65 | 44.71 | 28.43 |
| 2041 | 64.91 | 58.13 | 55.29 | 43.82 | 27.22 |
| 2042 | 64.99 | 57.79 | 54.78 | 42.82 | 25.98 |
| 2043 | 65.1 | 57.52 | 54.35 | 41.89 | 24.83 |
| 2044 | 65.22 | 57.26 | 53.9 | 40.98 | 23.76 |
| 2045 | 65.35 | 56.98 | 53.44 | 40.08 | 22.73 |
| 2046 | 65.47 | 56.68 | 52.98 | 39.21 | 21.77 |
| 2047 | 65.61 | 56.41 | 52.57 | 38.38 | 20.85 |
| 2048 | 65.74 | 56.14 | 52.11 | 37.57 | 19.99 |
| 2049 | 65.89 | 55.86 | 51.67 | 36.77 | 19.17 |
| 2050 | 66.01 | 55.59 | 51.24 | 35.97 | 18.39 |

**Table A3.** Policies and Unavoided Emissions Cost (USD Trillion Gtons $CO_2$.eq/Year) through Simulated Period

| Years | Baseline Case | Announced Policies Type 1 | Announced Policies Type 2 | 2.0 °C Scenario | 1.5 °C Scenario |
|---|---|---|---|---|---|
| 2023 | 149.9916 | 149.9916 | 149.9916 | 149.9916 | 149.9916 |
| 2024 | 150.1126 | 149.3382 | 148.9752 | 147.2086 | 142.8768 |
| 2025 | 150.3546 | 148.7574 | 148.0314 | 144.474 | 136.1492 |
| 2026 | 150.6208 | 148.1524 | 147.0634 | 141.7878 | 129.7604 |
| 2027 | 150.9838 | 147.6684 | 146.168 | 139.1984 | 123.7588 |
| 2028 | 151.3226 | 147.1602 | 145.321 | 136.6574 | 118.096 |
| 2029 | 151.7582 | 146.7004 | 144.4256 | 134.1164 | 112.7478 |
| 2030 | 152.218 | 146.2164 | 143.6512 | 131.648 | 107.6416 |
| 2031 | 152.6778 | 145.7808 | 142.8284 | 129.228 | 102.85 |
| 2032 | 153.1134 | 145.2968 | 141.933 | 126.7838 | 98.2762 |
| 2033 | 153.5732 | 144.7644 | 141.0134 | 124.3638 | 93.896 |
| 2034 | 154.033 | 144.3046 | 140.1906 | 121.9922 | 89.782 |
| 2035 | 154.4686 | 143.8206 | 139.3436 | 119.6448 | 85.8616 |
| 2036 | 155.001 | 143.3366 | 138.4482 | 117.3458 | 82.1832 |
| 2037 | 155.4366 | 142.8768 | 137.6012 | 115.0952 | 78.65 |
| 2038 | 155.848 | 142.3202 | 136.5848 | 112.7236 | 75.1652 |
| 2039 | 156.211 | 141.7152 | 135.5926 | 110.4246 | 71.874 |
| 2040 | 156.6466 | 141.1586 | 134.673 | 108.1982 | 68.8006 |

| | | | | | |
|---|---|---|---|---|---|
| 2041 | 157.0822 | 140.6746 | 133.8018 | 106.0444 | 65.8724 |
| 2042 | 157.2758 | 139.8518 | 132.5676 | 103.6244 | 62.8716 |
| 2043 | 157.542 | 139.1984 | 131.527 | 101.3738 | 60.0886 |
| 2044 | 157.8324 | 138.5692 | 130.438 | 99.1716 | 57.4992 |
| 2045 | 158.147 | 137.8916 | 129.3248 | 96.9936 | 55.0066 |
| 2046 | 158.4374 | 137.1656 | 128.2116 | 94.8882 | 52.6834 |
| 2047 | 158.7762 | 136.5122 | 127.2194 | 92.8796 | 50.457 |
| 2048 | 159.0908 | 135.8588 | 126.1062 | 90.9194 | 48.3758 |
| 2049 | 159.4538 | 135.1812 | 125.0414 | 88.9834 | 46.3914 |
| 2050 | 159.7442 | 134.5278 | 124.0008 | 87.0474 | 44.5038 |

**Table A4.** Policies and Avoided Emissions Cost (USD Trillion. Gtons $CO_2$.eq/Year) through Simulated Period

| Years | Baseline Case | Announced Policies Type 1 | Announced Policies Type 2 | 2.0 ºC Scenario | 1.5 ºC Scenario |
|---|---|---|---|---|---|
| 2023 | 0.0084 | 0.0084 | 0.0084 | 0.0084 | 0.0084 |
| 2024 | -0.1126 | 0.6618 | 1.0248 | 2.7914 | 7.1232 |
| 2025 | -0.3546 | 1.2426 | 1.9686 | 5.526 | 13.8508 |
| 2026 | -0.6208 | 1.8476 | 2.9366 | 8.2122 | 20.2396 |
| 2027 | -0.9838 | 2.3316 | 3.832 | 10.8016 | 26.2412 |
| 2028 | -1.3226 | 2.8398 | 4.679 | 13.3426 | 31.904 |
| 2029 | -1.7582 | 3.2996 | 5.5744 | 15.8836 | 37.2522 |
| 2030 | -2.218 | 3.7836 | 6.3488 | 18.352 | 42.3584 |
| 2031 | -2.6778 | 4.2192 | 7.1716 | 20.772 | 47.15 |
| 2032 | -3.1134 | 4.7032 | 8.067 | 23.2162 | 51.7238 |
| 2033 | -3.5732 | 5.2356 | 8.9866 | 25.6362 | 56.104 |
| 2034 | -4.033 | 5.6954 | 9.8094 | 28.0078 | 60.218 |
| 2035 | -4.4686 | 6.1794 | 10.6564 | 30.3552 | 64.1384 |
| 2036 | -5.001 | 6.6634 | 11.5518 | 32.6542 | 67.8168 |
| 2037 | -5.4366 | 7.1232 | 12.3988 | 34.9048 | 71.35 |
| 2038 | -5.848 | 7.6798 | 13.4152 | 37.2764 | 74.8348 |
| 2039 | -6.211 | 8.2848 | 14.4074 | 39.5754 | 78.126 |
| 2040 | -6.6466 | 8.8414 | 15.327 | 41.8018 | 81.1994 |
| 2041 | -7.0822 | 9.3254 | 16.1982 | 43.9556 | 84.1276 |
| 2042 | -7.2758 | 10.1482 | 17.4324 | 46.3756 | 87.1284 |
| 2043 | -7.542 | 10.8016 | 18.473 | 48.6262 | 89.9114 |
| 2044 | -7.8324 | 11.4308 | 19.562 | 50.8284 | 92.5008 |
| 2045 | -8.147 | 12.1084 | 20.6752 | 53.0064 | 94.9934 |
| 2046 | -8.4374 | 12.8344 | 21.7884 | 55.1118 | 97.3166 |
| 2047 | -8.7762 | 13.4878 | 22.7806 | 57.1204 | 99.543 |
| 2048 | -9.0908 | 14.1412 | 23.8938 | 59.0806 | 101.6242 |
| 2049 | -9.4538 | 14.8188 | 24.9586 | 61.0166 | 103.6086 |
| 2050 | -9.7442 | 15.4722 | 25.9992 | 62.9526 | 105.4962 |

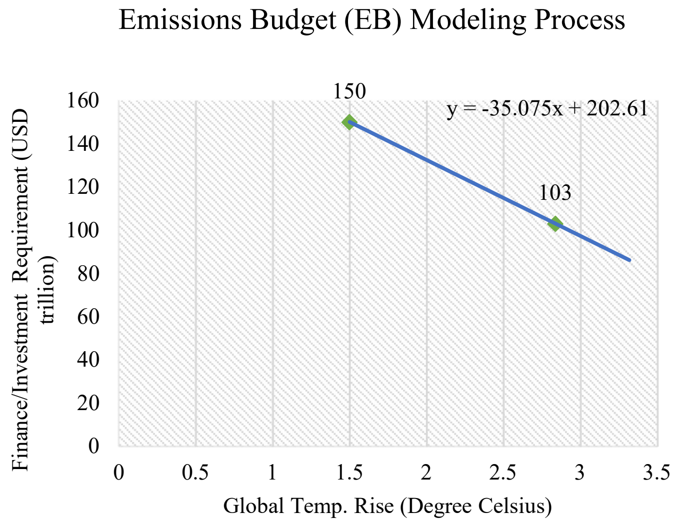


**Figure A6.** Different Simulated Policies versus Global Temperature Rise

**Table A5.** Summary of Policies, with Global Temp. Rise (ºC) against Financial/ Investment Requirements

| Scenarios | Global Temp. Rise (ºC) | Finance Requirement (USD Trillion) |
|---|---|---|
| Baseline Case | 3.32 | 86.1 |
| 1.5 ºC Scenario (net-Zero scenario) | 1.5 | 150 |
| 2.0 ºC Scenario | 2.0 | 132.5 |
| Announced Policies Type 2 (planned scenario) | 2.62 | 103 |
| Announced Policies Type 1 | 3.05 | 95.8 |

**Table A6.** Highlight of EB Modelling Steps

| S/N | Steps | Highlights |
|---|---|---|
| 1 | Selection of relevant policy scenarios | Based on the appendix, Table A1 |
| 2 | Identification of emissions costs | Based on Tables A3 and A4 |
| 3 | Assigning monetary values to the emissions cost flows per annum. | Based on Tables A3 and A4 |
| 4 | Estimation of emissions cost based on emissions cost flows per annum from each policy scenario. | Based on Tables A3 and A4 |
| 5 | Estimation of emission cost discount rate | Based on equation 2.10 |
| 6 | Calculation of the net present value of each investment based on the emissions cost. | Based on equation 2.5 |
| 7 | Calculate cost profitability/benefit index and payback period. | Based on equation 2.9 |

**Table A7.** Key Terms Consideration

| Finance Term | Study Adapted Term | Definition |
|---|---|---|
| N/A | Unit base cost of emissions removal | The cost of reducing or removing 1 ton of $CO_2$ eq, defined by equation (2.3) |
| Non-discounted cash flow | Unavoided emissions cost | The cost needed to reduce the total $CO_2$ eq at that period |
| Discounted cash flow | Avoided emissions cost | The cost savings as a result of action taken to reduce the total $CO_2$ eq at that period. |
| Profitability Index | Cost-benefit index | The benefit of the investment in terms of the ratio between the NPV to the required investment for a policy scenario |

N/A – Not Applicable

# Appendix A3 (Energy Model)

Data Statement for $CO_2$ Emissions Calibration in EN-ROADS:

The data sources utilized for calibrating $CO_2$ emissions per contributing resources are as follows:

1. Fossil fuels throughout 1990-2021 are the World Energy Balances and World Energy Statistics Datasets 1990-2020 [484], Friedlingstein et al.'s Global Carbon Budget [484], and BP's data [69].
2. The IEA World Energy Outlook [43] is used to align $CO_2$ emissions projections until 2050, while the SSP Database [485] and NGFS Scenario Portal [486] are employed to align $CO_2$ emissions projections until 2100.
3. The LUH2 v2e dataset [487], known as Land Use Harmonization2 data, is utilized to adjust land use modifications spanning from 1990 to 2100 accurately. The LUH2 v2e utilizes historical data spanning from 1990 to 2015 and subsequently incorporates SSP2 projections for the subsequent years.
4. The $CO_2$ emissions resulting from land use and forestry were adjusted using the average of many models from 1990 to 2021, based on data provided by Friedlingstein et al. in the Global Carbon Budget report of 2022 [484]. From that point onwards, the estimates were derived using NGFS Current Policies [486].

Emissions, GDP, and Population – Baseline Values

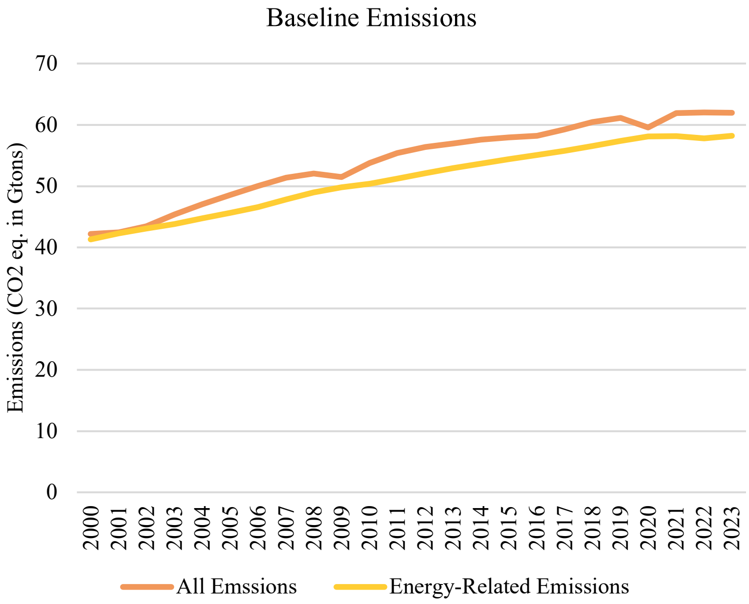


**Figure A7.** Values for Baseline Emissions

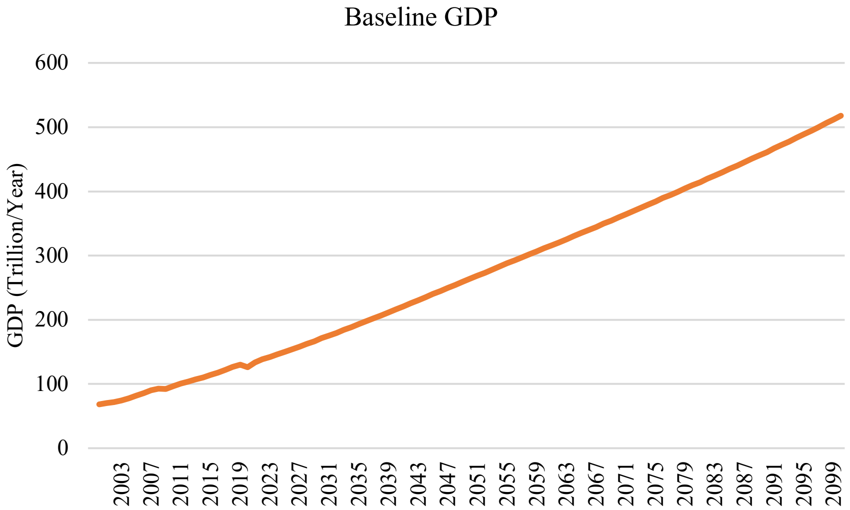
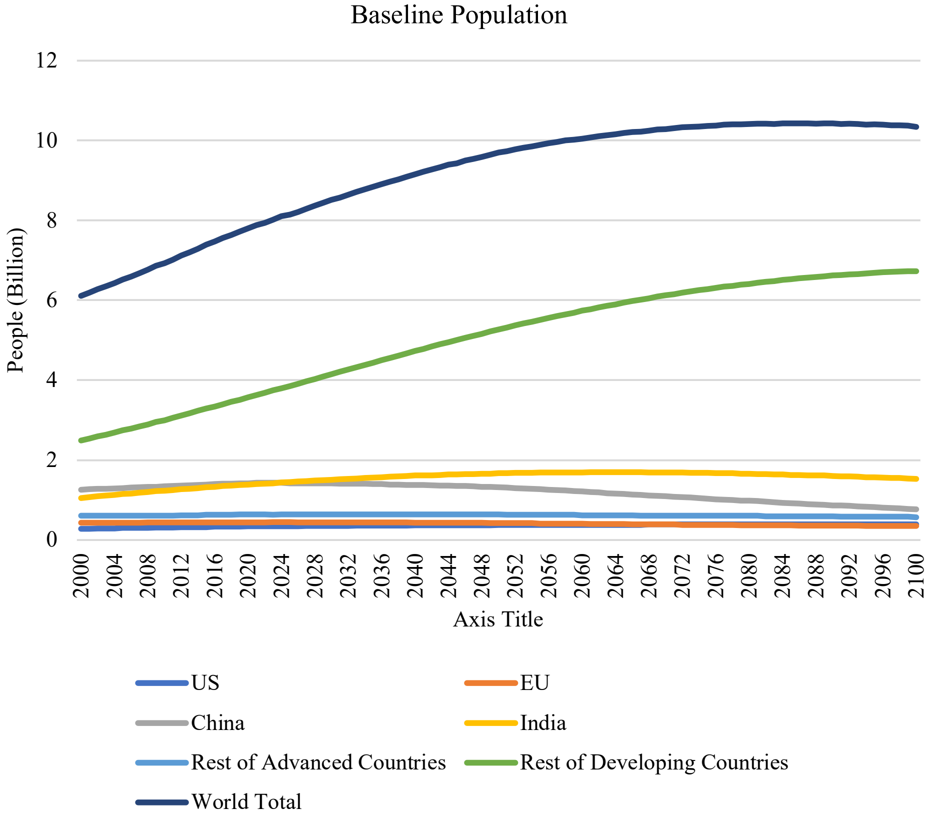
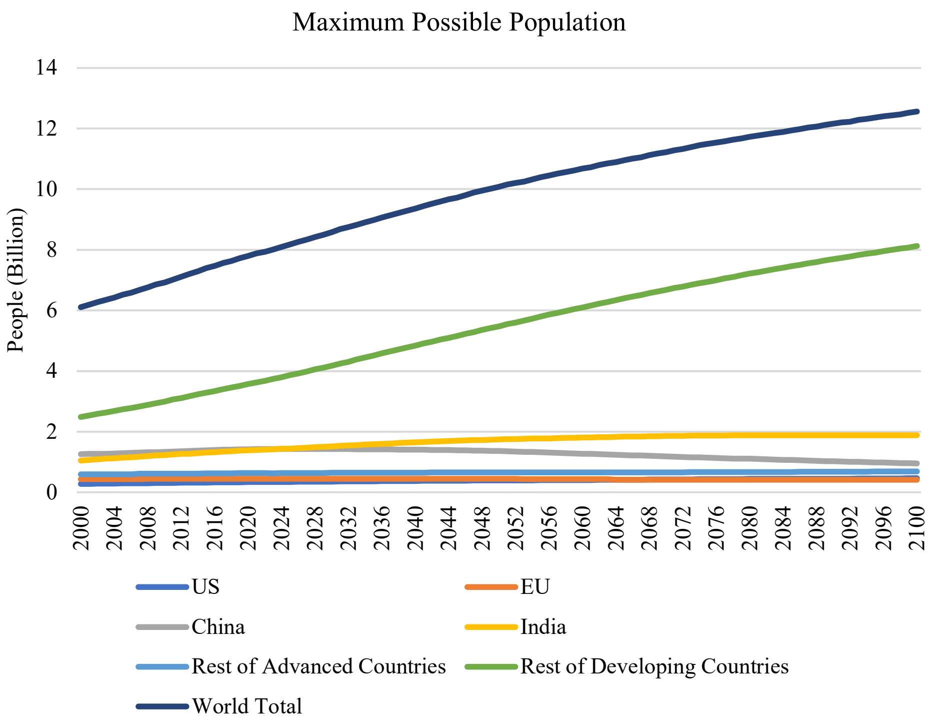


**Figure A8.** Values for Baseline GDP



(a) Baseline



(b) Maximum Possible

**Figure A9.** Values for Population

## Energy Profile per Technology from the Scenarios

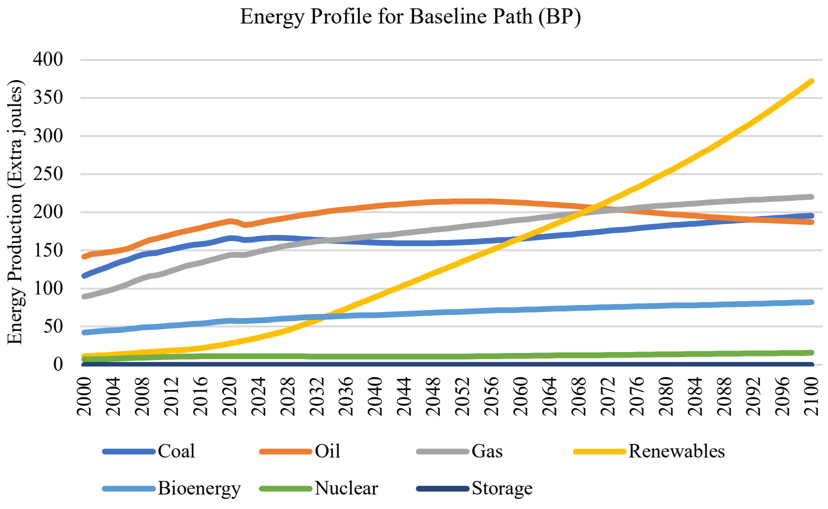


**Figure A10.** Energy Profile for Baseline Path (BP)

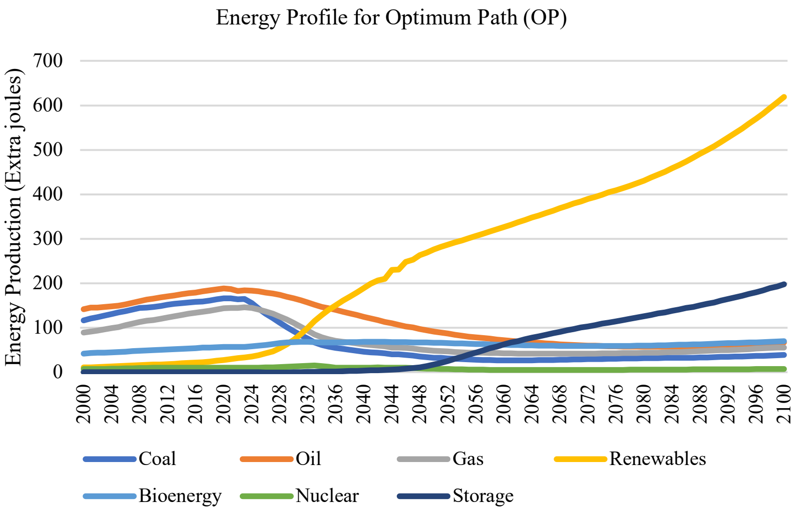


**Figure A11.** Energy Profile for Optimum Path (OP)

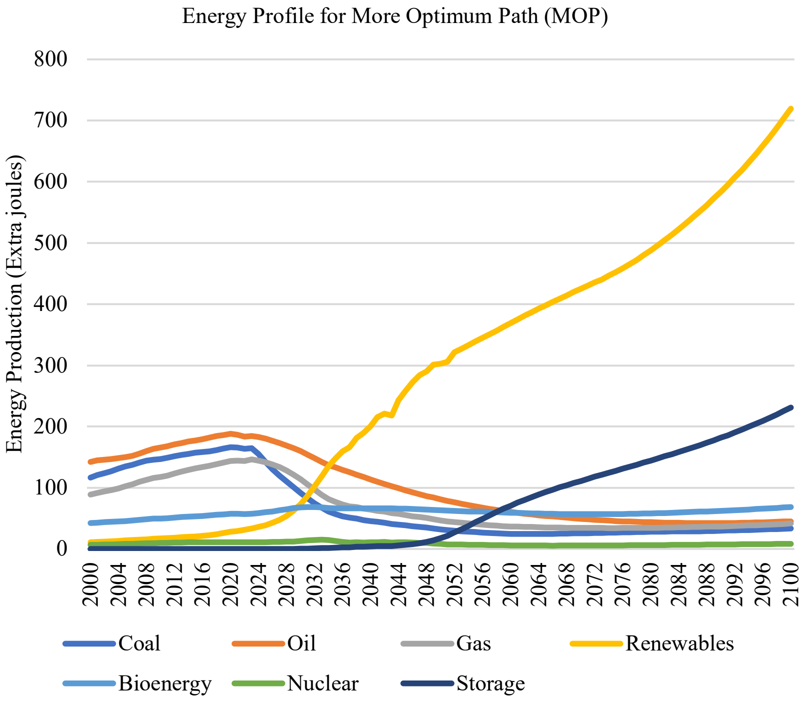


**Figure A12.** Energy Profile for More Optimum Path (MOP)

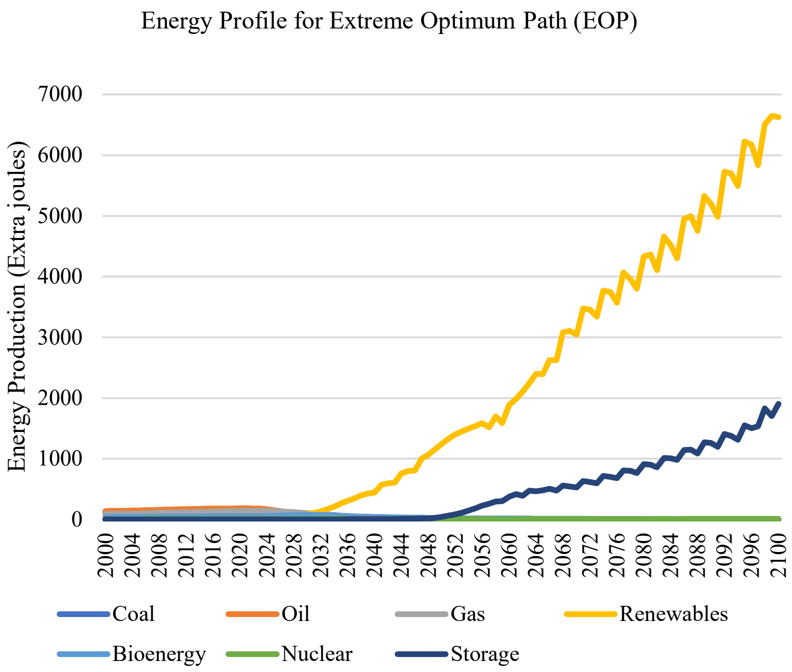


**Figure A13.** Energy Profile for Extreme Optimum Path (EOP)

**Table A8.** Current Path (3.3$^0$C Scenario)

| Year | RE Only in Global Mix (%) | RE + Storage Breakthrough in Global Mix (%) | CO2 Emissions per annum (Gtons.CO2 eq./year) | Global Energy Generation from RE (Extra joules/Year) |
|---|---|---|---|---|
| 2023 | 5.63 | 5.64 | 58.24 | 33.63 |
| 2024 | 5.89 | 5.89 | 58.85 | 35.64 |
| 2025 | 6.17 | 6.17 | 59.45 | 37.78 |
| 2030 | 8.02 | 8.02 | 61.83 | 51.72 |
| 2035 | 10.4 | 10.4 | 63.54 | 69.74 |
| 2040 | 12.7 | 12.7 | 65.05 | 88.79 |
| 2045 | 14.8 | 14.81 | 66.50 | 108.14 |
| 2050 | 16.8 | 16.79 | 67.83 | 127.53 |
| 2055 | 18.6 | 18.6 | 69 | 146.72 |
| 2060 | 20.3 | 20.29 | 69.97 | 165.84 |
| 2065 | 21.9 | 21.93 | 70.75 | 185.29 |
| 2070 | 23.6 | 23.57 | 71.37 | 205.76 |
| 2075 | 25.3 | 25.26 | 71.83 | 227.86 |
| 2080 | 27 | 27.03 | 72.1 | 251.94 |
| 2085 | 28.9 | 28.85 | 72.19 | 277.95 |
| 2090 | 31.1 | 31.14 | 72.17 | 306.55 |
| 2095 | 32.7 | 32.73 | 72.07 | 338.16 |
| 2100 | 34.7 | 34.69 | 71.93 | 371.91 |

**Table A9**. Optimistic Path (2.0$^0$C Scenario)

| Year | RE Only in Global Mix (%) | RE + Storage Breakthrough in Global Mix (%) | CO$_2$ Emissions per annum (Gtons.CO$_2$ eq./year) | Global Energy Generation from RE (Extra joules/Year) |
|---|---|---|---|---|
| 2023 | 5.63 | 5.63 | 58.19 | 33.66 |

| | | | | |
|---|---|---|---|---|
| 2024 | 6.09 | 6.09 | 57.33 | 35.85 |
| 2025 | 6.74 | 6.74 | 55.91 | 38.78 |
| 2030 | 13.9 | 14 | 48.09 | 72.84 |
| 2035 | 28.1 | 28.5 | 39.44 | 140.26 |
| 2040 | 37.3 | 38.1 | 33.95 | 189.14 |
| 2045 | 44.5 | 45.7 | 29.08 | 231.09 |
| 2050 | 51.1 | 54.2 | 25.50 | 276.47 |
| 2055 | 53.3 | 60.3 | 22.99 | 301.35 |
| 2060 | 54.6 | 65.1 | 21.33 | 326.79 |
| 2065 | 55.6 | 68.4 | 20.21 | 352.87 |
| 2070 | 56.4 | 70.8 | 19.73 | 379.46 |
| 2075 | 56.7 | 72.5 | 19.69 | 404.26 |
| 2080 | 57.1 | 73.9 | 20.04 | 431.05 |
| 2085 | 57 | 74.7 | 20.76 | 466.27 |
| 2090 | 57.8 | 75.7 | 22.01 | 508.66 |
| 2095 | 58.2 | 76.5 | 23.20 | 558.89 |
| 2100 | 58.6 | 77.3 | 24.82 | 619.28 |

**Table A10**. More Optimistic Path ($1.5^0$C Scenario)

| **Year** | **RE Only in Global Mix (%)** | **RE + Storage Breakthrough in Global Mix (%)** | **$CO_2$ Emissions per annum ($Gtons.CO_2$ eq./year)** | **Global Energy Generation from RE (Extrajoules/Year)** |
|---|---|---|---|---|
| 2023 | 5.63 | 5.63 | 58.19 | 33.66 |
| 2024 | 6.09 | 6.09 | 57.06 | 35.85 |
| 2025 | 6.76 | 6.76 | 55.28 | 38.79 |
| 2030 | 14.12 | 14.21 | 44.55 | 73.46 |
| 2035 | 29.76 | 30.19 | 32.67 | 147.79 |
| 2040 | 39.70 | 40.54 | 24.49 | 200.97 |
| 2045 | 48.57 | 49.86 | 17.83 | 258.41 |
| 2050 | 54.82 | 58.00 | 12.95 | 302.76 |
| 2055 | 57.56 | 64.99 | 9.5 | 339.06 |
| 2060 | 58.81 | 70.08 | 7.1 | 368.94 |
| 2065 | 59.56 | 73.48 | 5.57 | 397.99 |
| 2070 | 60.01 | 75.71 | 4.56 | 425.12 |
| 2075 | 60.27 | 77.31 | 4.24 | 451.99 |
| 2080 | 60.76 | 78.75 | 4.16 | 487.95 |
| 2085 | 61.31 | 79.99 | 4.42 | 531.88 |
| 2090 | 61.79 | 81.04 | 5.01 | 583.54 |
| 2095 | 62.23 | 81.95 | 5.88 | 644.88 |
| 2100 | 62.68 | 82.82 | 7 | 719.09 |

**Table A11**. Extreme Optimistic Path (100% RE Scenario/$1.1^0$C Path)

| Year | RE Only in Global Mix (%) | RE + Storage Breakthrough in Global Mix (%) | CO2 Emissions per annum (Gtons.CO2 eq./year) | Global Energy Generation from RE (Extra joules/Year) |
|---|---|---|---|---|
| 2023 | 5.77 | 5.77 | 57.21 | 33.94 |
| 2024 | 6.56 | 6.56 | 54.31 | 36.83 |
| 2025 | 7.64 | 7.63 | 50.95 | 40.56 |
| 2030 | 21.89 | 22.00 | 33.19 | 90.04 |
| 2035 | 60.18 | 60.83 | 16.83 | 264.29 |
| 2040 | 78.84 | 79.78 | 7.56 | 447.45 |
| 2045 | 89.27 | 90.32 | 1.5 | 797.69 |

|  |  |  |  |  |
|---|---|---|---|---|
| 2050 | 91.60 | 94.89 | -1.98 | 1245.87 |
| 2055 | 86.4 | 96.9 | -3.79 | 1541.79 |
| 2060 | 81.8 | 98.1 | -5.35 | 1889.01 |
| 2065 | 82.2 | 98.8 | -6.37 | 2395.17 |
| 2070 | 84.5 | 99.2 | -7.08 | 3044.1 |
| 2075 | 83.8 | 99.4 | -7.30 | 3750.35 |
| 2080 | 82.3 | 99.6 | -7.13 | 4331.68 |
| 2085 | 81.2 | 99.7 | -6.61 | 4300.1 |
| 2090 | 80.2 | 99.7 | -5.69 | 5198.03 |
| 2095 | 79.9 | 99.8 | -4.46 | 6223.46 |
| 2100 | 75.5 | 99.8 | -2.77 | 6627.27 |

**Table B1.** Summary of Strategies Used in the Simulation.

| Module (Variable) | Elements | Techno-economic and Socio-economic Indicators | Units |
|---|---|---|---|
| $E_S$ | 1. Renewables<br>2. Oil<br>3. Coal<br>4. Natural gas<br>5. Nuclear<br>6. Bioenergy<br>7. Carbon pricing and energy standards<br>8. New-Zero Carbon Technology Breakthrough | 1. Renewables (R)<br>i. Renewables tax/subsidy (R1)<br>ii. Renewables cost reduction breakthrough (R2)<br>iii. Energy storage breakthrough (R3)<br>2. Oil (O)<br>i. Oil tax/subsidy (O1)<br>ii. Reduction in new oil infrastructure (O2)<br>iii. % Reduction in oil infrastructure (O3)<br>3. Coal (C)<br>i. Coal tax/subsidy (C1)<br>ii. Reduction in new coal infrastructure (C2)<br>iii. % Reduction in coal utilization (C3)<br>iv. Acceleration in coal plan retirement (C4)<br>4. Natural gas (NG)<br>i. Natural gas tax/subsidy (NG1)<br>ii. Reduction in new natural gas infrastructure (NG2)<br>iii. Year to reduce natural gas infrastructure (NG3)<br>5. Nuclear (NU)<br>i. Nuclear tax/subsidy (NT1)<br>ii. Nuclear cost reduction breakthrough (NT2)<br>iii. Nuclear breakthrough year (consequence protection) (NT3)<br>6. Bioenergy (BI)<br>i. Bioenergy tax/subsidy (BI1)<br>ii. Bioenergy cost reduction breakthrough (BI2)<br>iii. Bioenergy breakthrough year (achieving zero emission in its process) (BI3)<br>iv. Reduction in new bioenergy infrastructure (BI4)<br>7. Carbon price (CP)<br>i. Initial Carbon price (CP1)<br>ii. Final Carbon price (CP2)<br>iii. Carbon pricing to bioenergy emissions (CP3)<br>iv. Carbon pricing for Carbon Capture and Storage (CP4)<br>v. Clean electricity standards with identification of qualifying sources (CP5)<br>vi. % Target of Clean electricity (CP6)<br>vii. Emissions performance standard (CP7)<br>8. New-Zero Carbon Technology Breakthrough | Table B2 |
| $T_{ee}$ | 1. Energy efficiency<br>2. Electrification | 1. Energy Efficiency (TEE)<br>i. New transport energy efficiency (TEE1)<br>2. Electrification (TE)<br>A. Road and Rail<br>i. % Purchase cost for electric transport subsidy and charging infrastructure (TE1)<br>ii. Limit to sales of fuel-powered transport (TE2)<br>B. Air and Water<br>i. Limit to sales of fuel-powered transport (TE3) | Table B2 |
| $B_{ee}, I_{ee}$ | 1. Energy efficiency<br>2. Electrification | 1. Energy Efficiency (BIEE)<br>ii. New building and industry energy efficiency (BIEE1)<br>iii. Rate of building and industry retrofitting (BIEE1)<br>2. Electrification (BIE1) | Table B2 |

| | | | |
|---|---|---|---|
| | | iv. % Purchase cost for electric equipment subsidy (BIE1)<br>iii. Limit to sales of fuel-powered equipment (BIE2) | |
| $G_{p,GDP}$ | 1. Population<br>2. Economic growth | 1. Population (P)<br>i. Population changes until the year 2100 (P1)<br>2. Economic growth (EG)<br>i. Long-term economic growth (EG1)<br>ii. Near-term economic growth (EG2)<br>iii. Transition time (EG3) | Table B2 |
| $LFI_e$ | 1. Deforestation<br>2. Methane and Other Gases | 1. Deforestation (D) Increment/Reduction (D1)<br>2. Methane and other gases (M) Increment/Reduction (M1) | Table B2 |
| $LFI_e$ | 1. Afforestation | 1. Afforestation (A)<br>i. % Available land used for afforestation (A1)<br>ii. Time to secure land for afforestation (A2)<br>iii. Afforestation planting time (A3) | Table B2 |
| $C_{CCS}$ | 1. Technology-Induced Carbon removal | 2. Technology-Induced (B) Carbon removal by technology<br>i. Direct air carbon capture and storage (B1)<br>ii. Enhanced mineralization (B2)<br>iii. Enhanced mineralization start year (B3) | Table B2 |

**Table B2.** Scenario Inputs

| Module (Variable) | Strategies and Indicators | Unit | BP | OP | MOP | EOP |
|---|---|---|---|---|---|---|
| $E_S$ | Renewables (R) | | | | | |
| | R1 | $/kWh | 0 | - 0.05 | -0.05 | -0.05 |
| | R2 | % | 0 | 0 - 50 | 50 | 50 |
| | R3 | % | 0 | 0 - 50 | 50 | 50 |
| | Oil (O) | | | | | |
| | O1 | $/boe | 0 | 17 | 85 | 85 |
| | O2 | % | 0 | 0 - 48 | 100 | 100 |
| | O3 | % | 0 | 0 - 10 | 100 | 100 |
| | Coal (C) | | | | | |
| | C1 | $/tce | 0 | 21 | 98 | 98 |
| | C2 | % | 0 | 0 - 50 | 100 | 100 |
| | C3 | % | 0 | 0 - 50 | 100 | 100 |
| | C4 | Year | 0 | 2023 | 2023 | 2023 |
| | C5 | % Per Year | - | 0 - 10 | 10 | 10 |
| | Natural gas (NG) | | | | | |
| | NG1 | $/Mcf | 0 | 1 | 5 | 5 |
| | NG2 | % | 0 | 0 | 100 | 100 |
| | NG3 | Year | 0 | 2023 | 2023 | 2023 |
| | Nuclear (NU) | | | | | |
| | NT1 | $/kWh | 0 | 0 | 0.07 | 0.07 |
| | NT2 | % | 0 | 0 | 0 | 0 |
| | NT3 | Year | 2030 | 2030 | 2030 | 2030 |
| | Bioenergy (BI) | | | | | |
| | BI1 | $/boe | 0 | 0 | -25 | -25 |
| | B12 | % | 0 | 0 | 50 | 50 |
| | B13 | Year | 2030 | 2030 | 2030 | 2030 |
| | B14 | % | 0 | | 100 | 100 |
| | Carbon price (CP) | | | | | |
| | CP1 | $/ton $CO_2$ | 5 | 100 | 120 | 250 |
| | CP2 | Year | 2100 | 2023 | 2023 | 2023 |
| | CP3 | Period (number of years) | 0 | 10 | 10 | 10 |
| | CP4 | $/ton $CO_2$ | 0 | 0 | 0 | 0 |
| $T_{ee}$ | Energy Efficiency (TEE) | | | | | |
| | TEE1 | %/Year | 0.5 | 2.7 | 3.5 | 5.0 |
| | Electrification (TE) | | | | | |
| | Road and Rail | | | | | |
| | TE1 | % of the purchase cost | 0 | 20 | 50 | 50 |
| | TE2 | % | 100 | 100 | 100 | 100 |
| | Air and Water | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | TE3 | % | 100 | 100 | 100 | 100 |
| $B_{ee}, I_{ee}$ | Energy Efficiency (BIEE) | | | | | |
| | BIEE1 | % Per Year | 1.2 | 2.8 | 3.2 | 4.0 |
| | BIEE2 | % Per Year | 5 | 5 | 5 | 5 |
| | Electrification (BIE1) | | | | | |
| | BIE1 | % of the purchase cost | 0 | 0 | 50 | 50 |
| | BIE2 | % | 100 | 100 | 100 | 100 |
| $G_{p,GDP}$ | Population (P) | | | | | |
| | P1 | Billion people by 2100 | 12.4 | 12.4 | 12.4 | 12.4 |
| | Economic growth (EG) | | | | | |
| | EG1 | % Per Year | 1.5 | 2.5 | 2.5 | 2.5 |
| | EG2 | % Per Year | 2.5 | 2.5 | 2.5 | 2.5 |
| | EG3 | Period (number of years) | 75 | 75 | 100 | 100 |
| $LFI_e$ | Deforestation (D) | | | | | |
| | Deforestation and Mature Forest Degradation (D1) | % Per Year | 0 | -10 | -10 | -10 |
| | Methane and Other Gases (M) | | | | | |
| | Methane and other gases (decrease/increase) M1 | % | 100 | 0 | -46 | -100 |
| $LFI_e$ | Afforestation (A) | | | | | |
| | A1 | % | 0 | 100 | 44 | 97 |
| $C_{CCS}$ | Technology-Induced (B) | | | | | |
| | Carbon removal by technology | | | | | |
| | B1 | % | 0 | 36 | 100 | 100 |
| | B2 | % | 0 | 0 | 100 | 100 |
| | B3 | Year | 2030 | 2030 | 2030 | 2030 |

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# Completed Training Plan

Joseph Samuel Akpan
Durban University of Technology (DUT)

## Summary of Master's Learning Activities

| Learning Activity | ECTS | Institute/Organization | Year |
|---|---|---|---|
| General research-related competencies<br>• Introduction to Research Ethics (mandatory)<br>• Thesis Writing Workshop Series<br>• Research workshops | - | DUT Faculty of Engineering and University Research Centres | 2022 |
| B) Research Project/Thesis related competencies<br>• System Dynamics training using VENSIM.<br>• Courses and Modules | 30 | Erasmus Mobility Program at the University of Valladolid, Spain | 2022 - 2023 |
| Career development competencies<br>• Erasmus Traineeship | 12 | Institute of Sustainable Processes, Spain | 2022 - 2023 |
| Conferences and Research Participation<br>• Poster Presentation<br>• Conference Presentation with proceedings | - | | 2022, 2023 |
| Total | 42 | | |

One European Credit Transfer and Accumulation System (ECTS) credit typically represents a minimum of 25 hours of work.

## List of Courses Taken

| Classes/Modules | Credits Hours |
|---|---|
| System Dynamics. Modelling and Simulation in Engineering | 6 ECTS |
| The Environment and Renewable Energy | 6 ECTS |
| Simulating Pollution Management and Treatment Processes | 3 ECTS |
| Environmental Biotechnology | 3 ECTS |
| Master's Assignment | 9 ECTS |
| Spanish Language (A1 Level) | 3 ECTS |
| Company Internship/External Practical | 12 ECTS |
| Final Master's Thesis | Full Research |

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Certificat

Certificate

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Promoting the highest ethical standards in the protection of biomedical research participants

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Joseph Akpan

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Contact: josephsamuelakpan@gmail.com, 22176142@dut4life.ac.za, and oludolapoo@dut.ac.za