energies

MDPI

Review

Renewable Energy Source Utilization Progress in South Africa: A Review

Abayomi A. Adebiyi * and Katleho Moloi

Department of Electrical Power Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Durban 4001, South Africa; katlehom@dut.ac.za
* Correspondence: abayomia@dut.ac.za

Abstract: Renewable energy has emerged as a promising solution to address the challenges of climate change, energy security, and socio-economic development. South Africa, with its abundant renewable energy resources, has made significant strides in the utilization of renewable energy over the past decade. This paper provides a comprehensive review of the progress of renewable energy advancement in South Africa, examining the policies, initiatives, and achievements in various renewable energy sectors. This study explores the country's transition from a heavily coal-dependent energy system to a diversified and sustainable energy mix. It analyses the growth of renewable energy technologies, such as wind power and solar photovoltaic (PV), highlighting the key milestones, challenges, and opportunities. Furthermore, this paper discusses the role of government support, regulatory frameworks, and private sector investments in driving renewable energy deployment in South Africa. Finally, it identifies the prospects and potential areas for further advancement in the renewable energy sector. This review aims to contribute to the understanding of South Africa's renewable energy journey and provides valuable insights for policy-makers, researchers, and stakeholders involved in the sustainable energy transition.

Keywords: South Africa; renewable energy utilization; policy; challenges; energy mix; environmental sustainability

check for updates

Citation: Adebiyi, A.A.; Moloi, K. Renewable Energy Source Utilization Progress in South Africa: A Review. *Energies* **2024**, *17*, 3487. https://doi.org/10.3390/en17143487

Academic Editors: Francesco Nocera and Piotr Borowski

Received: 4 June 2024
Revised: 1 July 2024
Accepted: 9 July 2024
Published: 16 July 2024

1. Introduction

A developing country's ability to generate, transmit, and consume appropriate electric power is significantly linked to its socioeconomic and infrastructure expansion [1–7]. Being Africa's largest electric power consumer, South Africa has established itself as one of the most advanced countries on the continent [1,8]. Although South Africa possesses limited proven oil and gas reserves, it compensates for this shortfall by leveraging its extensive coal deposits to meet its energy requirements. As of 2022, coal has dominated the South African energy mix, contributing to 80% of South Africa's overall primary energy consumption. Renewable energy technologies' (wind, solar PV, and CSP) contribution increased in 2022 to a total of 6.2 GW installed capacity and provided 7.3% of the total energy mix, as depicted in Figures 1 and 2 [9]. Despite the effectiveness of coal in power generation, its use has contributed to South Africa being ranked amongst the top ten greenhouse gas emitters globally, emitting 680 kg of CO_2 per USD 1000 of GDP [10–13].

In response, South Africa has embarked on efforts to reduce CO_2 emissions whilst simultaneously developing renewable energy sources (RESs) [14–16]. This review discusses the development of solar photovoltaic (SPV), wind energy, biomass, and geothermal energy as prominent RESs in South Africa, highlighting the progress made and challenges encountered in the process. This article delves into the overview of non-renewable energy in South Africa and the historical background of South Africa's power generation in order to provide an in-depth comprehension of the expansion of renewable energy sources (RESs) in the country. Moreover, it offers a thorough analysis of the development of RESs in South

Africa, building on the extant literature in [1,16], which only provides an overview of the issues and advancements in the South Africa RES sector. The use of solar PV, wind energy, biomass, and geothermal energy is prioritized for the generation of both power and heat. Reliable databases (SCOPUS, Web of Science, and Google Scholar) provided the extant literature for this study.

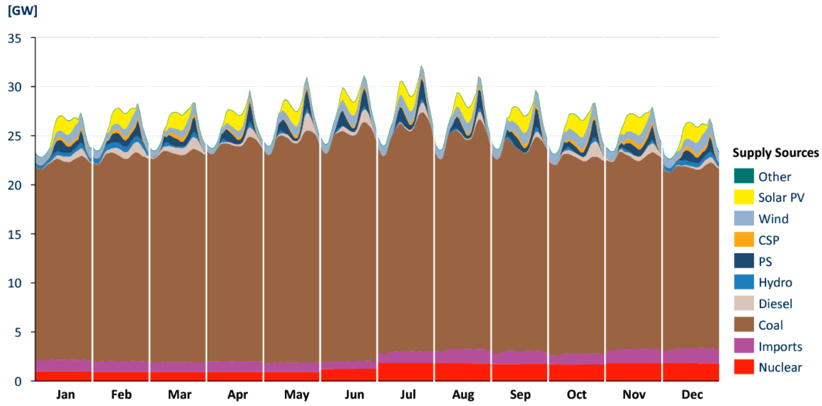

Figure 1. South Africa's energy mix composition [9].

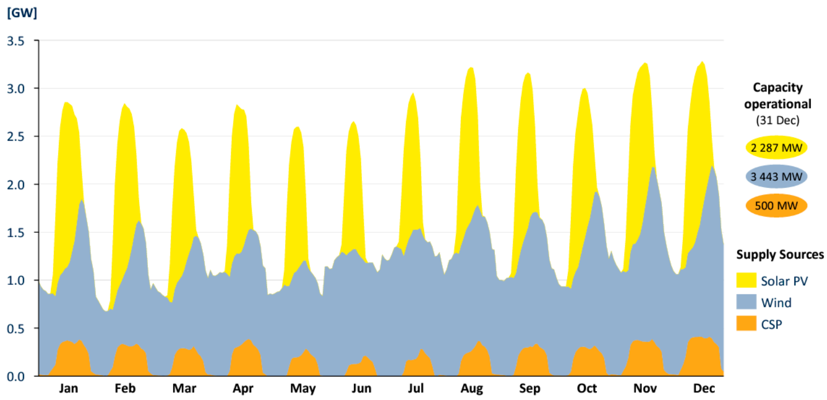

Figure 2. The renewable energy technology energy mix in South Africa [9].

2. Non-Renewable Energy in South Africa

Non-renewable energy typically refers to energy sources such as fossil fuels (coal, oil, and natural gas) and nuclear power, which are finite and cannot be naturally replenished on a human time-scale [17]. In the case of South Africa, non-renewable energy plays a significant role in the country's energy mix, particularly with coal being the dominant source of electricity generation. Despite the abundant accessibility of this fossil fuel, South Africa and many other countries persist in seeking alternative energy sources to mitigate the detrimental impacts of non-renewable energy on environmental well-being.

These impacts are far-reaching, environmentally destructive, and pose a threat to the economy [18–21]. The drive for sustainable development on a global scale has altered the outlook on the energy sector. According to [22–25], a significant element influencing economic growth has been found to be the increase in carbon dioxide emission levels. The creation of programs like the Kyoto Protocol and Sustainable Energy for All, a United Nations initiative aimed at mitigating the gradual degradation of the world and reducing climate change, is due to the global recognition of greenhouse gas emissions resulting from the combustion of fossil fuels.

3. The Historical Context of Power Generation in South Africa

The unveiling of an arc light in Cape Town in 1860 is considered to be the first recorded incidence of electricity in South Africa [1]. The first electric street lights in the country were then installed in the mining town of Kimberly, which helped mining activities at night [26,27]. The enhanced throughput made possible by the Cape Town mines' electrification after the discovery of gold in Johannesburg in 1886 led to the construction of Johannesburg's first electricity plant in 1889 [28]. Subsequently, municipality lightning started from Rondebosch in 1892 and rapidly spread to numerous South African cities in the ensuing years [29]. South Africa experienced a remarkable surge in electricity generation and distribution during the period between the 1890s and the 1900s, primarily to support mining operations and illuminate urban areas.

However, this growth was accompanied by exorbitant electricity prices due to the limited capacity and inefficiency of the power utilities, along with inadequate connectivity amongst consumers. As a solution to these challenges, the idea of establishing a centralized power enterprise began to emerge, leading to the eventual founding of the Victoria Falls Power Company (VFP) in 1906 [1,30]. In 1915, VFP established a central control centre at Simmerpan, which had a combined installed capacity exceeding 160 megawatts (MW) across its thermal power plants [27,31]. Recognizing the significance of electricity, the Transvaal colonial administration introduced The Power Act, granting the government the authority to acquire privately owned electric enterprises after a span of thirty-five years. Subsequently, the Electricity Act of 1922 was enacted following a study on electrification in South Africa, which ultimately led to the establishment of the Electricity Supply Commission (ESCOM) in March 1923 [31].

ESCOM played a crucial role in electrifying the railway network and establishing additional power stations throughout South Africa. In 1925, ESCOM constructed the Malieveld Spruit hydropower station as a temporary solution while the Sabie River Gorge plant, which became operational in 1927, was being developed [32]. These two plants marked ESCOM's initial ventures in power generation, and they served as important milestones. To meet the growing electricity demand resulting from the gold rush, ESCOM proceeded to commission additional power plants. Electricity sales for ESCOM reached an impressive 800 million units by 1929 [31]. To meet the increasing power demands, ESCOM took significant steps such as acquiring VFP in 1948 and Kimberley's central power station in 1950. In 1951, ESCOM established the Rural Electrification Department to deliver electricity to rural communities in South Africa.

Alongside the establishment of new power plants, ESCOM pursued a strategy of acquiring independent plants, bolstering its existing accomplishments and responding to the need for a more integrated power generation and transmission infrastructure. This expansion continued until South Africa faced a severe drought in early 1983 [1]. In conjunction with other contributing factors, the drought led to a decline in ESCOM's power output, resulting in a subsequent increase in electricity tariffs. In response, the government established the Electricity Council, comprising fifteen individuals who were entrusted with the task of overseeing ESCOM's operations [33].

To increase power generation further, ESCOM underwent a re-organization, and a revised Electricity Act was introduced in 1987. This led to an expansion of the company's customer base and a name change from ESCOM to ESKOM, derived from the former name, ESCOM/EVKOM, by combining the acronyms [33]. Considering ESKOM's concerns regarding deregulated electricity pricing and non-compliant consumers, the government amended the Electricity Act and appointed a National Electricity Regulator to assume the responsibilities of the Electricity Council board. This modification helped to ameliorate ESKOM's financial issues to a degree. However, ESKOM advised the government of an impending power supply shortfall in the years ahead if an urgent revamping of the power stations was not commenced. The government seemed to dismiss the need for capital investment expansion in ESKOM because it was considering privatizing or corporatizing ESKOM and because it wanted to distribute power more widely rather than generate it. As a result, in 2007, ESKOM started to be inconsistent and less efficient in power delivery. After the government realized its error, it issued a public apology.

As a result of increasing energy demands in the years that followed, power disruptions increased in frequency [34,35]. Moreover, because of the ageing of several coal plants, there was a growing need for frequent maintenance, often requiring plants to temporarily go off-grid for repairs. This has been exemplified by incidents such as the turbine unit failure at the Duhva power plant in 2011, which caused a blast resulting in a loss of 600 MW of power from the grid. Consequently, the incident significantly escalated both the plant's maintenance expenses and its overall productivity costs [36]. Similarly, in 2018, a tragic accident occurred at Lethabo Power Station Unit 5 when the steam pressure from the boiler ruptured [37]. Furthermore, it would take at least another two years to repair the catastrophic hydrogen explosion that occurred in Unit 4 of the Medupi coal-fired power plant in 2022 [38].

In 2022, South African power plants experienced a significant surge in breakdowns, resulting in a staggering 19,052 megawatts of generating capacity being rendered inactive because of malfunctions. This amount accounts for approximately 40% of the total generating capacity in the country [39]. Despite possessing a total installed capacity exceeding 58 gigawatts (GW) to serve a population of 60.5 million people, ESKOM has not achieved its objective of delivering uninterrupted and affordable energy to all South Africans. Furthermore, the country is grappling with mounting debt, which has surpassed USD 263.9 billion [40–42]. While ESKOM continues to face developmental challenges, it is important to acknowledge that the state-owned electric utility company remains one of the most reliable and efficient power providers in sub-Saharan Africa. In fact, ESKOM surpasses the power generation capabilities of the continent's most populous nation, Nigeria, which has a total installed capacity of less than 5 GW [43,44] and Egypt's 595 GW installed power generation capacity to a population of 109.3 million [45,46].

4. South Africa's Carbon Footprint

The total amount of greenhouse gas emissions, mostly carbon dioxide (CO_2), brought about by human activity is referred to as a country's "carbon footprint". These emissions have an impact on global warming and climate change. Several industries, including the generation of power, transportation, industrial operations, and agriculture, have an impact on South Africa's carbon footprint. Moreover, South Africa's high reliance on coal for the generation of power has significantly increased its carbon footprint. The country ranks 14th globally in terms of carbon emissions, making it the highest emitter in Africa. Additionally, South Africa accounts for 33% of total air pollution in Africa. In 2020, the nation experienced a 1.5% increase in carbon emissions [47–49].

Figure 3 depicts the global carbon project analysis of South Africa's per capita CO_2 emissions. Promoting renewable energy sources, enhancing energy efficiency, putting emission reduction plans into practice, and taking part in global accords and actions to address climate change are all ways that South Africa is engaging to minimize its carbon footprint.

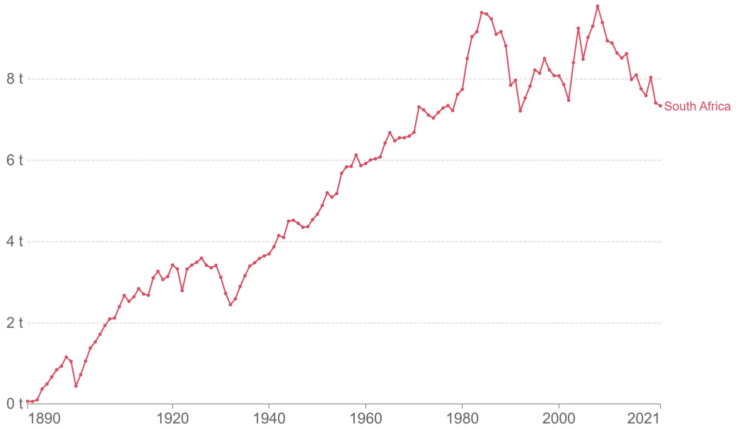

Figure 3. South Africa per capital CO_2 emissions [50].

A national advancement renewable energy source technology policy statement outlining South Africa's plan of generating 10 terawatt-hours (TWh) of power from RES was issued in 2003. In 2011, an integrated resource plan was unveiled, setting a new objective to increase the share of RESs in the energy mix to 17,800 MW by 2030. In addition, the Renewable Energy Independent Power Producer's Program (REIPPP) was launched in 2011 to promote private investments and expedite the nation's energy transformation. The program focuses on lowering CO_2 emissions, creating economic growth possibilities, and increasing generating capacity [51,52]. ESKOM, the predominant electricity producer in South Africa, currently supplies 96% of the country's total electricity production. The remaining 4% is generated by municipalities and independent power providers. ESKOM's power generation portfolio comprises 14 coal-fired power plants, one nuclear power plant, and a limited number of gas-fired stations. Furthermore, ESKOM operates a small number of hydroelectric power units alongside its other facilities [53]. The burning of coal, which is a finite and environmentally hostile resource for South Africa's power generation, can be substantially mitigated by shifting towards RESs as a viable alternative. Embracing renewable energy has the potential to not only reduce the country's carbon footprint but also create new employment opportunities, thereby bolstering the economy of the nation. The next sections will explore the prospects for renewable energy sources (RESs) in South Africa. However, before examining each energy source in detail, it is essential to compare the different technologies in terms of their life-spans. Notably, research conducted by the National Renewable Energy Laboratory (NREL) reveals that solar photovoltaic (PV) technology boasts the longest life-span amongst renewable energy sources [54]. Table 1 offers a comprehensive overview of the life-cycles of major technologies.

Table 1. A comparison of the life-cycles of RES technologies [54].

RES Type	System Useful Life
Wind energy	20 years
Biomass energy	20 to 30 years
Geothermal energy	24 years
Photovoltaics energy	25 to 40 years

These RES technologies offer additional social benefits, such as improved health outcomes and technological advancements, contingent on a few fundamental considerations. The fundamental factors in each nation's development are its social features. The social implications of each resource with its proportion are mentioned in Table 2.

Table 2. Social impact of RES technologies.

RES Technology	Social Impact	Proportion
Wind energy	Aesthetics	Minimal
Biomass energy	Impaired biodiversity	Minimal
Geothermal energy	Noise	Minimal
Photovoltaics energy	Contaminants	Minimal

5. Wind Energy

The application of wind energy in South Africa dates back several decades. Early settlers in the country, who were predominantly farmers, relied on wind energy for many years to pump water for irrigation and domestic purposes. These farmers' exceptional agricultural yields were made possible by this method [55]. The country's energy mix has, however, largely relied on coal because of its low cost and wide availability, making the integration of wind energy difficult. To supply home and agricultural water demands, some 30,000 windmill installations had been installed by the early 1990s throughout South Africa's rural and agrarian regions. However, the use of wind energy to generate power for commercial use has not yet attracted much attention [56].

The capacity of the wind power sector in South Africa has gradually evolved, enabling the nation to achieve its targets for renewable energy. With its ability to cut carbon emissions and diversify the mix of energy sources, wind power has come to be recognized as a clean and sustainable energy source. The 1995 Diab's wind atlas was the first attempt to quantity the wind energy potential in South Africa. It offers detailed estimates and analyses of the country's wind resources, helping to identify suitable locations for wind energy projects and furthering the development of the wind energy sector in South Africa [57]. In 2008, a second wind atlas mapping effort was conducted in South Africa, focusing on analysing wind speeds at heights above 10 m to identify prime locations for wind energy exploitation. The resulting map highlighted the most favourable areas for wind energy generation throughout the country.

With optimistic assumptions, the analysis suggested a potential of generating 50 GW of wind energy. However, taking a more conservative approach, it was estimated that South Africa could potentially harness approximately 6 GW of wind energy. These findings provided valuable insights into the country's wind energy potential and helped guide decision-making and planning in the renewable energy sector [58]. In response to the discrepancies observed in previous wind energy atlas mapping efforts, the South African government, through the South African Wind Energy Project (SAWEP), undertook the development of a comprehensive Wind Atlas for South Africa (WASA) in 2018. This updated wind atlas provides detailed information on the mean wind speed throughout the country and the mean power density across different provinces. The data presented in the WASA is particularly valuable for investors interested in establishing large-scale wind farms in South Africa as it assists in identifying optimal locations with favourable wind resources.

The WASA serves as a crucial tool in supporting informed decision-making and facilitating the development of the wind energy sector in the country [59]. Figure 4 depicts the WASA high-resolution map of South Africa's energy potential. In 2002, ESKOM commissioned the 27 MW Klipheuwel wind farm, the first wind farm in South Africa, on the country's west coast as part of the government's commitment to fostering the application of RESs. The wind farm served as an experimental site to explore the potential of wind energy for power generation. The wind farm supplies about 20,000 South Africans with 86,000 MWh per annum and has successfully achieved a reduction of 24,080 tonnes in annual carbon emissions and a total reduction of 481,600 tonnes in lifetime carbon emissions [60]. Multiple wind farms have since been built all around South Africa over the years. Because of favourable wind resources, provinces including the Western Cape, Eastern Cape, and Northern Cape have experienced major wind farm installations [61].

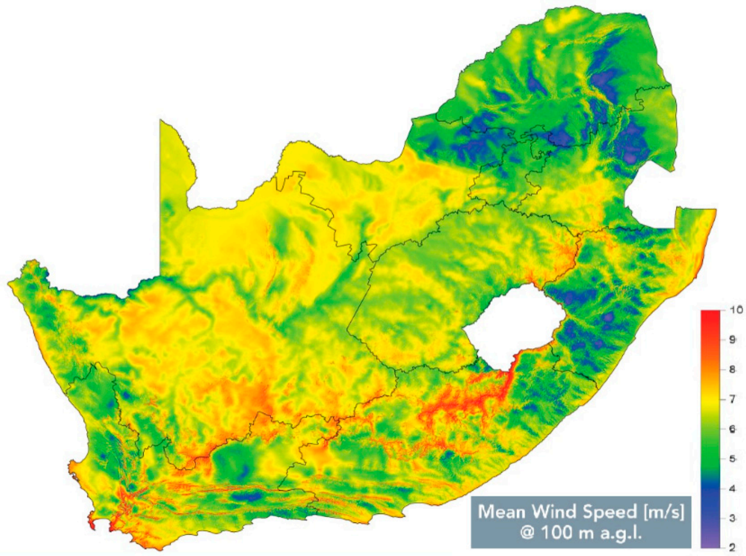

Figure 4. Wind Atlas South Africa (WASA) wind energy map [62].

Since the 27 MW Klipheuwel wind farm came into service, the installed wind power capacity in South Africa has grown rapidly, reaching 3357 MW in 2022, and it is projected to reach 17,742 MW by 2030 [63,64]. While South Africa's wind energy potential is being harnessed, there are still technical and environmental issues that must be resolved if the industry is to continue expanding.

5.1. Technical Difficulties

One of the issues hindering the widespread deployment of wind energy is the problem of situating wind farms. These power plants are often situated in remote areas, posing difficulties in connecting them to the power grid since wind farms are typically required to be in specified zones. Consequently, a significant portion of the generated power is lost because of inadequate grid infrastructure. To overcome this issue, expensive transmission lines are typically required to be erected, linking the wind farms to urban centres, thereby increasing the overall installation costs of the wind farm [65].

The variability in wind speed, upon which wind power relies, introduces potential technical issues such as voltage fluctuations, even in the presence of a stable grid infrastructure. The power output of wind power plants is directly proportional to changes in wind speed, and managing these fluctuations is costly [65]. This variability results in an excess or insufficient supply of power, ultimately causing disruptions in the power grid [66]. Despite the undeniable benefits of widespread wind energy adoption in South Africa, it is crucial to address the existing technical difficulties before the sector can thrive effectively.

5.2. Environmental Difficulties

Wind energy in South Africa faces various environmental challenges that need to be considered and addressed for the sustainable development of the technology. Some of these challenges include avian and bat mortality, habitat fragmentation, noise and visual impact, and land and water use. Wind turbines pose a risk to birds and bats, particularly if they are located in migration corridors or areas with high biodiversity. Collisions with rotating turbine blades can result in bird and bat fatalities [1,67,68]. Additionally, wind farm construction can lead to habitat fragmentation, disrupting natural ecosystems and potentially affecting wildlife populations.

It is important to consider the potential impacts on habitats and implement mitigation measures, such as establishing buffer zones and corridors, to preserve ecological connectivity and minimize habitat fragmentation [69]. Wind turbines also produce noise during operation, which can have adverse effects on local communities, wildlife, and even marine ecosystems if located near coastlines. Visual impact is also a concern, as large-scale wind farms can alter the aesthetic value of landscapes. The visual impact of wind energy infrastructure can be influenced by various factors, including colour contrast, size, proximity to residential areas, presence of flashing shadows, and duration of operation. These factors collectively define the "visual impact zone", according to contemporary planning standards.

By considering the distance and carefully selecting a wind farm's placement, it is possible to assess and plot the degree of visual impact. Proper planning, stakeholder engagement, and adherence to noise regulations can help mitigate these challenges [70,71]. Wind farms require significant land area for installation, which can potentially compete with other land uses, such as agriculture or conservation. Researchers have long been interested in understanding the competition that arises from land utilization for agriculture and energy purposes. Different studies have focused on examining the suitability of different types of land, including arable and marginal land, for both agricultural and energy-related activities [72,73].

To effectively tackle these environmental challenges, a comprehensive approach is necessary, encompassing rigorous environmental impact assessments, active stakeholder engagement, strategic site selection based on ecological considerations, and the implementation of efficient mitigation measures. By prioritizing environmental sustainability, South

Africa can optimize the benefits of wind energy whilst minimizing any potential adverse impacts on the environment. This can be achieved through the careful execution of thorough environmental impact assessments and the implementation of policies that address these challenges, such as appropriate siting practices and robust monitoring protocols [73]. Table 3 presents the net wind energy output in South Africa between 2013 and 2023. This indicates the growth in generation in line with government policy.

Table 3. South Africa's wind energy output from 2013 to 2023 [74].

Year	Generated Power (MW)
2013	257
2014	569
2015	1079
2016	1473
2017	2094
2018	2094
2019	2094
2020	2516
2021	2495
2022	3163
2023	3442

6. Solar Energy

South Africa, like many other African countries, possesses abundant solar energy resources. The Northern Cape region stands out with its remarkable Direct Normal Irradiation (DNI) reaching over 3200 kWh/m^2, while the KwaZulu-Natal region experiences a more moderate yearly DNI of around 1400 kWh/m^2. In recent years, there have been numerous applications of solar energy, both direct and indirect, in South Africa. This section explores the utilization of solar energy in the country, focusing on solar photovoltaics and solar water heating.

6.1. Solar Photovoltaic (SPV)

Solar photovoltaic (SPV) utilize the photo-electric effect to directly convert solar irradiation into electrical energy [75,76]. The photo-electric effect involves the emission of electrons from a material's surface when it is exposed to light of the appropriate wavelength, with these materials typically being referred to as semi-conductors [77,78]. SPV cells are devices designed to harness the energy of sunlight and convert it into usable electricity. SPV technology is a widely adopted and rapidly growing renewable energy source worldwide, including in South Africa. SPV systems consist of solar panels, which are composed of multiple PV cells that contain semi-conductors, typically made of silicon. SPV offers several advantages, making it an attractive option for generating electricity, including the following:

(a) Renewable and Sustainable: Solar energy is abundant and inexhaustible, making it a renewable and sustainable source of power. The sun's energy is freely available, and the technology to capture and convert it into electricity is constantly improving [79–81].

(b) Low Environmental Impact: Solar PV produces electricity without emitting greenhouse gases or other harmful pollutants, resulting in significantly reduced environmental impacts compared with fossil fuel-based power generation. This helps to combat climate change and contributes to cleaner air and water [82–84].

(c) Versatility and Scalability: SPV systems can be installed on a variety of scales, ranging from small rooftop installations for residential homes to large-scale utility solar farms, generating outputs ranging from microwatts to megawatts. This versatility enables SPV to be deployed in a wide range of applications, from powering individual households to supplying electricity to remote buildings, communication systems, satellites, and spacecraft [85].

(d) Economic Benefits: SPV systems provide opportunities for job creation, both in the manufacturing and installation sectors. Direct, indirect, and influenced employment opportunities are amongst the employment possibilities provided by the SPV value-chain. These employment opportunities not only support the expansion of the renewable energy industry but also have favourable effects on job creation and economic growth. South Africa could possibly add to employment via the solar-powered economy, which would also lower greenhouse gas emissions and promote RESs in the energy mix. Furthermore, solar energy has the potential to reduce reliance on expensive imported fossil fuels, thereby enhancing energy security and promoting local economic development [86,87].

In South Africa, SPV has experienced significant growth in recent years, driven by factors such as declining costs, government support, and increasing awareness of the benefits of RESs. The country benefits from abundant solar resources, particularly in regions such as the Northern Cape, which has excellent solar irradiation levels. The South African government has implemented various initiatives and incentives, such as the Renewable Energy Independent Power Producer Procurement Program (REIPPPP), to promote the development of solar PV projects. SPV deployment in South Africa can offset electricity consumption, reduce reliance on the grid, and potentially enable the selling of excess electricity back to the grid through net metering or feed-in tariff schemes.

While solar PV offers numerous benefits, challenges do exist, including the intermittent nature of sunlight, the need for sufficient space for installations, and the initial investment costs. However, ongoing technological advancements and supportive policies continue to drive the growth and adoption of SPV in South Africa, contributing to a more sustainable and cleaner energy future [88,89]. According to the most recent statistics available from South Africa's Department of Energy (DoE), as shown in Table 4, the total installed capacity of SPV increased from 1350.6 MW in 2016 to 1961.4 MW in 2021 [90].

Table 4. South Africa's SPV output from 2016 to 2021 [90,91].

Year	Generated Power (MW)
2013	262
2014	1164
2015	1353
2016	2176
2017	3451
2018	4805
2019	4908
2020	5994
2021	6316
2022	6326
2023	6164

In recent times, South Africa has successfully installed several large-scale solar power plants, which has bolstered the country's rapidly expanding renewable energy industry. In the Northern Cape province alone, there are more than one hundred independent power producers, with a total capacity of 900 MW and over twenty projects connected to the grid. At the end of the first quarter of 2023, there was 6164 MW of installed solar PV capacity in South Africa, and it is expected to surpass 12 GW in the next ten years [92,93]. Of the current installed capacity, 2200 MW came from governmental procurement, mostly through the Renewable Energy Independent Power Producer Program (REIPPP), and 3964 MW is from private installation.

The residential sector utilizes 11% of the installed capacity, with 30% of the capacity consisting of systems smaller than 1 MVA, encompassing residential, commercial, and industrial applications, which constitutes the small-scale embedded generation. Utility-scale systems exceeding 50 MW make up 27% of the installed capacity, whereas systems in the 1 MW to 50 MW range contribute 32%. With 586 MW of installed capacity, the City of Johannesburg in the province of Gauteng ranks highest on the list of installations. The Northern Cape province's Pixley ka Seme district municipality is next, with 583 MW.

Taken as a whole, they both account for more than 20% of the country's installed SPV capacity. The City of Tshwane in Gauteng leads the list in terms of residential installations with 22,956 installations, closely followed by the City of Cape Town with 21,342 installations. With an average of 10.8 kWp per system, eThekwini in KwaZulu-Natal has the largest average residential systems amongst them, followed by the City of Cape Town at 7 kWp [94]. Table 5 comprises a compilation of several solar photovoltaic projects across the country.

Table 5. South Africa's major SPV installations [95].

Project Name	Installed Capacity (MW)	Project Location	Energy Production (GWh)	Averted CO_2 Emissions (Tons/Year)	Energy Demand Supplied (Household)
Adams Solar Plant	82.5	Northern Cape province	167 GWh	171,700	100,000
Aggeneys Solar PV Park	46	Northern Cape province	117 GWh	90,600	20,000
Aries Solar Park	11	Northern Cape province	22 GWh	14,053	4900
Boshof Solar Farm	66	Free State province	132 GWh	98,700	30,000
De Aar project	175	Northern Cape province	195 GWh	84,554	76,000
Dreunberg Solar PV Park	75	Eastern Cape province	156 GWh	130,000	38,000
KaXu Solar One	100	Northern Cape province	400 GWh	315,000	65,000
Kalkbult Solar Station	75	Northern Cape province	150 GWh	130,000	35,000
Kotulo Tsatsi PV Farm	150	Northern Cape province	1800 GWh	750,000	320,000
Jasper Solar	96	Northern Cape province	180 GWh	145,000	80,000
Mulilo Prieska PV	180	Northern Cape province	220 GWh	160,000	80,000
Xina Solar One	100	Northern Cape province	400 GWh	205,763	65,000
Ilanga-1 CSP Plant	100	Northern Cape province	400 GWh	100,000	90,000
Lesedi Solar PV Plant	75	Northern Cape province	150 GWh	134,690	65,000
Letsatsi Solar Plant	75	Northern Cape province	150 GWh	134,690	65,000
Tom Burke PV Plant	66	Limpopo province	122 GWh	111,000	38,000
Greefspan II PV Plant	63	Northern Cape province	0.15 GWh	130,000	20,000
Paleisheuwel Solar Park	82.5	Western Cape province	153 GWh	140,000	48,000
Sishen PV Plant	94.3	Western Cape province	216 GWh	229,280	100,000

There has been impressive growth in South Africa's installed rooftop solar PV capacity. The increase from 983 MW in March 2022 to 4412 MW in June 2023 represents a remarkable 349% growth in just over a year. This surge in rooftop solar capacity suggests a growing interest in and adoption of renewable energy sources, likely driven by factors such as environmental concerns, cost savings, and advancements in solar technology. It is noteworthy that ESKOM, the state-owned electricity supplier in South Africa, has supplied these data, indicating a level of official recognition and monitoring of the country's renewable energy landscape. This trend aligns with global efforts to transition towards cleaner and more sustainable energy sources to mitigate the impacts of climate change.

The continued proliferation of rooftop solar PV installations in South African provinces, particularly in the Western Cape, Gauteng, and Kwa Zulu-Natal, is a noteworthy development. The increased affordability of solar technology is a key driver of this expansion, making it more accessible to a broader range of energy consumers. Eskom, South Africa's power utility, monitored and reported on the growth of rooftop solar PV capacity, indicating a growing recognition of the importance of renewable energy sources in the country's energy landscape.

The substantial growth from 983 MW in March 2022 to 4412 MW in June 2023 demonstrates a significant shift towards decentralized energy generation and a desire to harness clean and sustainable energy options [96]. This surge in rooftop solar adoption can have positive implications for energy resilience, reducing dependence on traditional grid infrastructure, and contributing to national efforts to address climate change by decreasing reliance on fossil fuels.

6.2. Solar Water Heating

Energy is used up significantly during the heating of water, and up to 40% of energy consumption in South Africa goes towards heating water. Unfortunately, most South Africans pay a high price for hot water, which is necessary to maintain personal and public health. Solar water heaters (SWHs) that use solar energy can assist in alleviating the South African energy issue. In South Africa, solar water heating offers an effective way to cut costs, conserve energy, and advance sustainable development. The usage of SWH systems is anticipated to increase, benefiting both homes and the environment, because of continued government initiatives and improved awareness [97,98]. Figure 5 depicts a map of South Africa's solar irradiation spread.

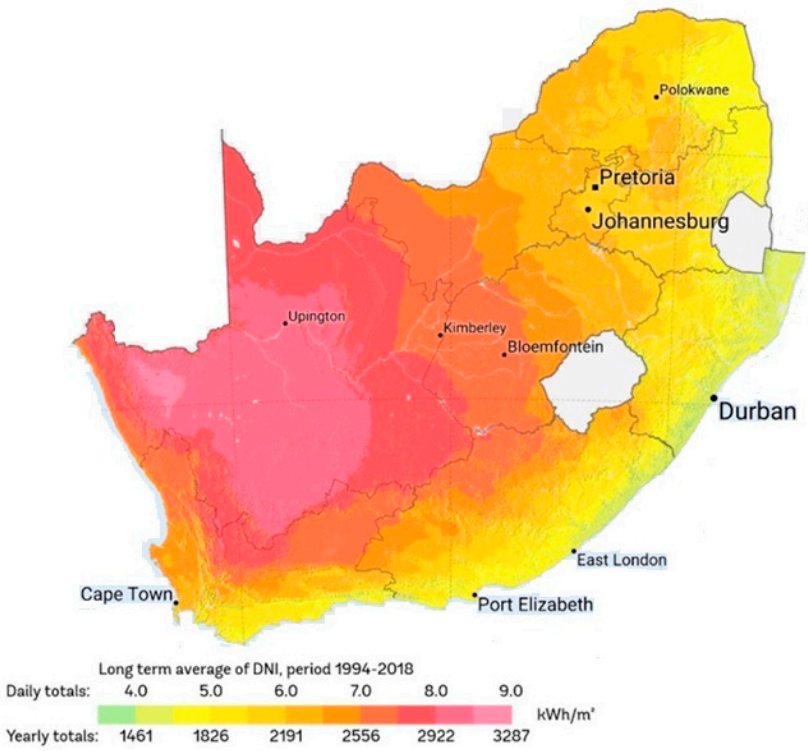

Figure 5. Map of South Africa's global horizontal irradiation [99].

6.3. Concentrated Solar Power

Globally, there is a growing interest in concentrated solar power (CSP) plants, with South Africa being a particularly notable adopter. South Africa, through the Renewable Energy Independent Power Producer Procurement (REIPPP) program, has played a crucial role in facilitating private investment in the implementation of large-scale CSP projects. The Redstone Solar Thermal Power Project, a 100 MW facility in the Northern Cape, is one of the major CSP projects in South Africa. This project incorporates molten salt energy storage, allowing it to generate 480,000 MW hours of electricity annually, even when the sun is not shining [100].

CSP systems use mirrors or lenses to concentrate sunlight, generating high-temperature thermal energy that is applicable in various ways. This thermal energy is versatile, allowing for conversion into power generation, material processing, process heat, and heating and cooling applications. The dual capability of CSP technology, producing both heat and electricity, makes it a flexible solution for diverse energy needs across various industries. Moreover, the incorporation of thermal energy storage technologies in CSP plants ensures continuous electricity generation even when solar irradiation is unavailable, thereby enhancing grid stability and reliability. CSP's adaptability positions it as a complementary element to other renewable energy sources like wind and PV power, contributing to the ongoing transition towards a more sustainable and renewable energy future.

Solar power towers (SPTs), parabolic dish collector systems (PDCSs), parabolic trough collector systems (PTCSs), and linear Fresnel reflectors (LFRs) are some of the technologies used in CSP. Furthermore, because of its benefits—which include increased efficiency, lower operating costs, and significant scale-up potential—the SPT has become a more significant CSP technology. Despite the advantages of CSP, a major problem facing all CSP technologies is the fluctuation in solar irradiation throughout the day and year [101–103]. This section compares the technologies and provides a thorough explanation of each CSP in relation to South Africa's potential for solar energy.

6.3.1. Parabolic Dish Collector Systems

The parabolic dish collector system (PDCS) comprises an energy generator, a Stirling engine at the centre of the dish, and parabolic reflectors in the form of dishes. These solar dishes automatically face the sun throughout the day to direct solar irradiation onto the Stirling engine. The system uses parabolic dishes with a concentration ratio of about 2000 to reach 9000 °C at their focal point and produce 200 bar working fluid pressure [103]. A parabolic dish collector typically has 50–120 square meters of surface area and a diameter of 6–10 m. These dish-reflecting surfaces are typically made of glass or plastic with aluminium or silver overlays. Mirrors made of silver on glass that have a thickness of around 1 mm exhibit the best performance. A certain quantity of iron is included in the glass to improve reflection. Mirrors composed of silver on iron-containing glass have a combined solar reflectivity and emittance value of between 90% and 94%. Figure 6 below presents a graphic illustration of a parabolic dish collector with a Stirling motor.

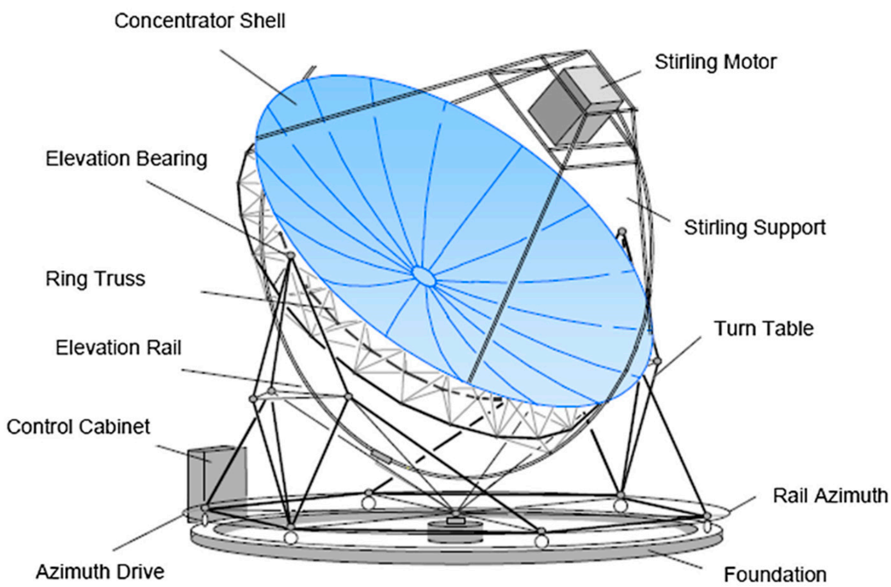

Figure 6. Parabolic dish schematic with a Stirling motor [104].

The technology of the parabolic dish collector system (PDCS) is advantageous for its ability to be deployed independently, making it suitable for areas that are not connected to the power utility grid, or regions with uneven and rough terrain. However, it comes with the following drawback: the inability to seamlessly integrate with thermal storage systems [1,105]. Moreover, the PDCS with a Stirling motor has an efficiency rate of 30% [103,106].

6.3.2. Parabolic Trough Collector Systems (PTCSs)

Parabolic trough collector systems (PTCSs) utilize a one-axis tracking mechanism, where parabolic mirrors aligned along a north–south or east–west axis track the Direct Normal Irradiance of the solar energy. Subsequently, these mirrors reflect the irradiation onto a central receiver system housing pressurized water, molten salt, or thermal oil. The produced heat is employed to generate steam, which in turn operates a steam engine for electricity generation. Subsequently, the utilized steam is condensed back into water and re-introduced into the system.

The operating temperature of the heat transfer fluid typically falls within the range of 400–600 °C, depending on the working fluid, while metal liquids have the capacity to reach temperatures of up to 900 °C [1,103,107]. The PTCS stands out as the most extensively employed system amongst CSP technologies because of its well-established technical advancement and stable performance. As of the conclusion of 2021, global CSP installations have reached a total capacity of 6.8 GW, with parabolic trough collector systems (PTCSs) representing over 80% of this figure, according to statistics [108]. Figure 7 below illustrates a parabolic trough collector system.

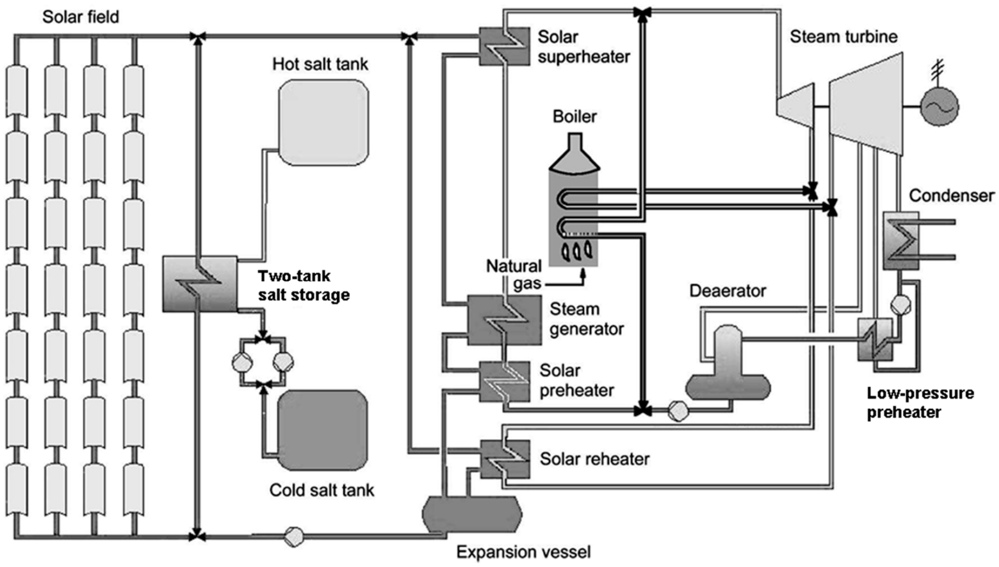

Figure 7. PTCS process flow schematic [109].

The South Africa Electricity Regulation Act of 2006 outlines the national electricity policy, providing a framework for power demand projections. The Act envisages an increase in generation capacity by 46 GW, with 24 GW coming from renewable energy sources, including CSP, aiming to achieve a preferred energy mix [110] and an augmented national installed capacity of 90 GW by 2030 [111,112]. The inclusion of CSP technology is motivated by the substantial solar energy potential in the country. Although there are currently a few PTCS-based CSP installations in existence, as indicated in Table 6, the full potential of CSP technologies has not been fully maximized at present.

Studies on the possibility of CSP generation in all of South Africa's provinces were conducted, as described in [113]. The research considered several variables, such as the amount of solar irradiation, the distance from current transmission lines, the topography of the province, and the environmental impact assessment. The results showed that the Northern Cape province was best suited for the widespread application of CSP technologies, with the Eastern Cape and the Free State provinces showing some degree of potential as well. The study avers that South Africa has a 500 GW potential CSP total generation capacity, especially if the Northern Cape province's solar resource is used to its full potential [110,113].

Table 6. CSP projects in South Africa.

CSP Projects	CSP Technology	Capacity (MW)	Location
Ilanga I	Parabolic trough	100	Northern Cape
ISCC Green Duba 1	Parabolic trough	43	Northern Cape
Kathu Solar Park	Parabolic trough	100	Northern Cape
KaXu Solar One	Parabolic trough	100	Northern Cape
Khi Solar One	Parabolic trough	50	Northern Cape
Xina Solar One	Parabolic trough	100	Northern Cape
Bokpoort CSP	Parabolic trough	50	Northern Cape

6.3.3. Linear Fresnel Reflector (LFR)

Linear Fresnel Reflector (LFR) solar power generation, as depicted in Figure 8, is a system designed to concentrate solar beam radiation onto a receiver tube positioned at the focal point of the Fresnel mirror. This concentration is achieved through the tracking movement of the FLR mirror to follow the sun's trajectory, generating a high-temperature working medium for thermal cycle power generation.

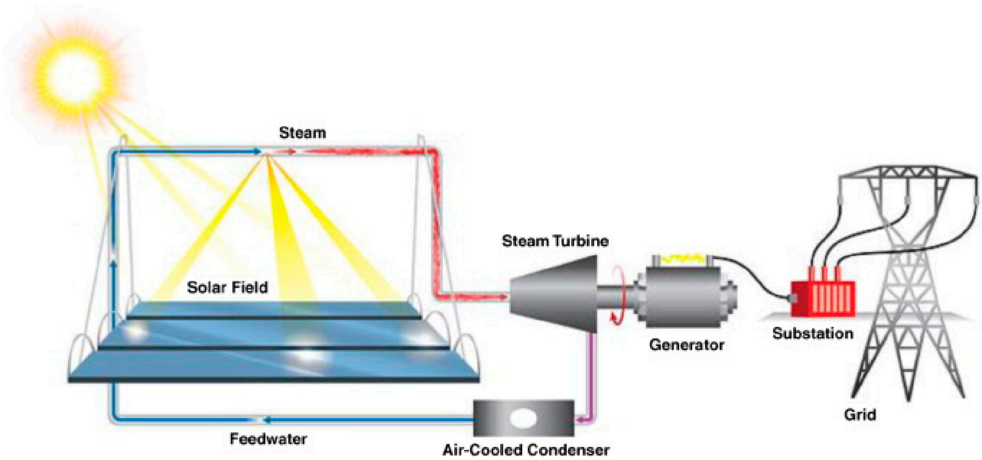

Figure 8. Fresnel reflector-integrated CSP plant [103].

Key components of the LFR power generation system include the linear reflective mirror, receiver tube, and transmission system. This system is essentially a condensed variant of the parabolic trough collector system (PTCS), in which a surface mirror takes the place of the conventional parabolic trough concentrator [101]. The mirror's characteristics include its proximity to the ground, low wind load, simple structure, intensive layout, and higher land-use efficiency. Additionally, the LFR system eliminates the need for vacuum treatment for the receiver tube, thus reducing both technical challenges and associated costs.

This results in a comparatively lower total system cost. However, it is worth noting that the system's low concentration ratio leads to a lower operational temperature, consequently affecting the overall system efficiency. A significant drawback of the Linear Fresnel Reflector (LFR) system lies in its substantial space requirement to avoid shading effects on the reflectors. While this issue can be mitigated by elevating the height of the absorber tower, such a modification would inevitably raise the overall cost of the system [114].

6.3.4. Solar Power Towers (SPTs)

Solar power towers (SPTs) utilize a heliostat field collector (HFC), which consists of solar tracking reflectors known as heliostats. Heliostats are mirrors, either flat or slightly concave, that track the sun in a two-axis movement. These heliostats reflect and concentrate solar irradiation onto a central receiver positioned at the top of a fixed tower [101,115]. In the central receiver, heat is absorbed by a heat transfer fluid (HTF), which then conveys the heat to heat exchangers driving a steam Rankine power cycle. Some operational commercial tower plants utilize Direct Steam Generation (DSG), while others employ various fluids, including molten salts, as both the HTF and storage medium [101].

The tower concept's concentrating power achieves exceptionally high temperatures, enhancing the efficiency of converting heat into electricity and reducing thermal storage costs. Moreover, this concept offers considerable flexibility, allowing designers to choose from a diverse range of heliostats, receivers, and transfer fluids. Some plants may feature multiple towers feeding into a single power block. Figure 9 presents a schematic layout of the solar tower power plant.

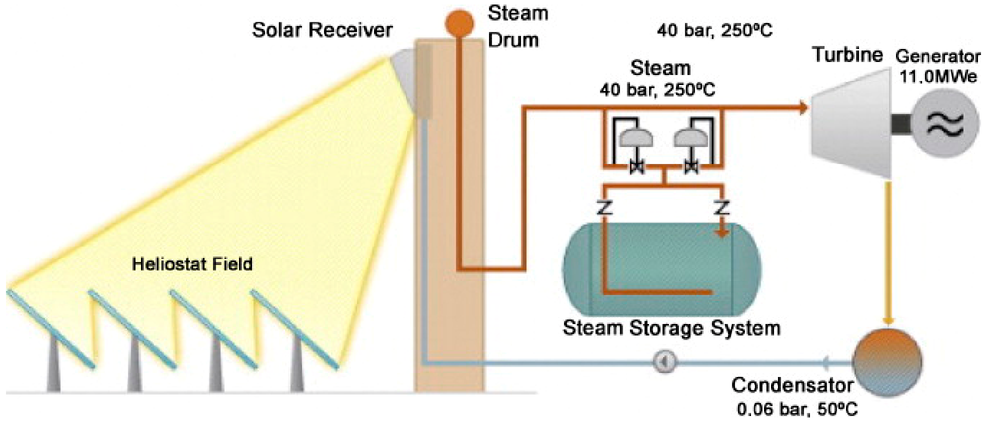

Figure 9. A schematic layout of a solar tower power plant [103].

6.3.5. Comparison

Table 7 provides a comparison of different CSP technologies based on basic criteria. With the potential to contribute at least 7% of global electricity needs by 2030 and 25% by 2050, under the projection of a high-energy-saving condition [116], CSP technologies possess substantial potential to address a portion of South Africa's future energy demand [117]. The anticipation is that the CSP market will experience rapid and continued expansion [103].

Table 7. CSP technology comparison.

Type of CSP	Capital Cost (USD/W)	Land Usage	Water for Cooling (L/MWh)	Heat Dynamic Efficiency (%)	Solar Concentration Ratio (C)
LFR	1.57	Medium	3000	Low	40
PDCS	2.91	Small	3000	High	45
PTCS	3.22	Large	Dry-cooled	Low	1000
SPT	4.62	Medium	1500	High	1500

The solar power tower (SPT) demonstrates the highest solar concentration ratio, as indicated in Table 7. The solar concentration ratio (C) is defined as the ratio of the concentrated flux on the receiver to the ambient flux from the sun. This ratio is calculated by dividing the receiver's area by the total area of the reflectors, assuming that the receiver is fully illuminated. The concentration ratio is a pivotal parameter in CSP plant performance, influencing power plant efficiency. Elevating the concentration ratio directs more sunlight into the collecting area, consequently leading to increased power output [118].

6.4. Technical Difficulties

Solar energy is a promising source of renewable energy for South Africa, given the abundant available sunlight. However, several technical difficulties need to be addressed in order to optimize its potential. This study found the following key challenges as an area of interest towards achieving South Africa's energy mix agenda:

(a) Grid Integration and Stability: Solar energy production is intermittent and variable, depending on weather conditions and time of day. This creates challenges for grid stability and reliability. The existing grid infrastructure may not be fully equipped to handle the large-scale integration of solar power, whilst upgrading and maintaining the grid can be costly and technically demanding. Effective energy storage systems, and storage technologies such as batteries, which are required to store excess solar energy and supply power during non-sunny periods are currently expensive and still developing [119,120].
(b) Geographical and Climatic Challenges: South Africa has abundant sunlight, but solar irradiation varies significantly across different regions. Optimal solar plant locations are often far from major urban centres, necessitating efficient transmission systems. Moreover, dust accumulation on solar panels can reduce their efficiency. Regular cleaning and maintenance are required, particularly in arid regions with high dust levels. High temperatures can also affect the efficiency of photovoltaic (PV) panels. In extremely hot climates, the efficiency of solar panels decreases [121].

Addressing these technical challenges requires a coordinated effort from the government, private sector, and research institutions to create a sustainable and efficient solar energy infrastructure in South Africa.

7. Conclusions

Despite South Africa's significant potential for renewable energy sources, coal remains its primary fuel source because of its low cost, although it is detrimental to the environment. The improved application of RESs is crucial for the nation, as the heavy reliance on coal is straining the existing coal-fired power plants. While wind and solar energy are viable options because of favourable wind speeds and high levels of annual solar radiation, the growth in renewable energy faces several challenges. These include environmental-, technological-, financial-, and policy-related issues. To address these issues and improve the integration of renewable energy into South Africa's energy mix, several recommendations are proposed. These recommendations include the following:

I. Enhance Policy and Regulatory Frameworks: The government needs to implement clear policies that establish clear long-term regulatory frameworks that support renewable energy development, providing stability and confidence for investors. The government needs to introduce financial incentives, such as tax breaks, grants, and subsidies, to encourage more investment in renewable energy projects, as well as to reduce bureaucratic delays in permitting and granting approval for renewable energy projects.
II. Upgrade Grid Infrastructure: The national grid could be upgraded by intentionally investing in modernizing and expanding the grid to better accommodate renewable energy inputs, thus ensuring stability and reliability. The country needs to develop and implement advanced energy storage systems to address the intermittency of renewable energy sources and provide a stable supply.
III. Explore Other Potentials: Further utilization of solar energy resources in South Africa can provide numerous benefits beyond the current major applications in solar PV, solar water heating (SWH), and concentrated solar power (CSP). Another potential application of solar energy, which remains under-utilized but could be highly beneficial for the country, is solar cooking using a solar cooker to harness sunlight for food processing. Adopting solar cooking technology could significantly reduce reliance on coal, thereby contributing to CO_2 mitigation and enhancing sustainability and energy efficiency in the country.

By implementing these recommendations, South Africa can overcome the challenges associated with renewable energy development and significantly enhance the integration of renewable sources into its energy mix, contributing to a more sustainable and resilient energy future. Future studies will carry out social and environmental impact analyses for various RES projects in particular provinces of South Africa. Focusing on these future research issues will support South Africa in its transition to a robust, sustainable, low-carbon energy system.

Author Contributions: Conceptualization, A.A.A.; methodology, A.A.A. and K.M.; software, A.A.A.; validation, A.A.A. and K.M.; formal analysis, A.A.A.; investigation, A.A.A.; resources, A.A.A. and K.M.; data curation, A.A.A.; writing—original draft preparation, A.A.A.; writing—review and editing, A.A.A. and K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Upon request, the corresponding author will provide the data used in this work. Restrictions on the disclosure of the tools used to process the data prevent the data from being made publicly available.

Acknowledgments: The responsibility for the content is solely on the authors.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of this study; in the collection, analysis, or interpretation of data; in the writing of this manuscript; or in the decision to publish the results.

References

1. Akinbami, O.M.; Oke, S.R.; Bodunrin, M.O. The state of renewable energy development in South Africa: An overview. *Alex. Eng. J.* **2021**, *60*, 5077–5093. [CrossRef]
2. Sehlapelo, T.; Inglesi-Lotz, R. Examining the determinants of electricity consumption in the nine South African provinces: A panel data application. *Energy Sci. Eng.* **2022**, *10*, 2487–2496. [CrossRef]
3. Bah, M.M.; Azam, M. Investigating the relationship between electricity consumption and economic growth: Evidence from South Africa. *Renew. Sustain. Energy Rev.* **2017**, *80*, 531–537. [CrossRef]
4. Azam, M. Relationship between energy; investment; human capital; environment, and economic growth in four BRICS countries. *Environ. Sci. Pollut. Res.* **2019**, *26*, 34388–34400. [CrossRef] [PubMed]
5. Mutumba, G.S.; Odongo, T.; Okurut, N.F.; Bagire, V. A survey of literature on energy consumption and economic growth. *Energy Rep.* **2021**, *7*, 9150–9239.
6. Azimoh, C.L.; Klintenberg, P.; Wallin, F.; Karlsson, B.; Mbohwa, C. Electricity for development: Mini-grid solution for rural electrification in South Africa. *Energy Convers. Manag.* **2016**, *110*, 268–277. [CrossRef]
7. Zebra, E.I.C.; van der Windt, H.J.; Nhumaio, G.; Faaij, A.P. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111036. [CrossRef]
8. Apergis, N.; Polemis, M.; Soursou, S.-E. Energy poverty and education: Fresh evidence from a panel of developing countries. *Energy Econ.* **2022**, *106*, 105430–105441. [CrossRef]
9. CSIR. Statistics on Power Generation in South Africa for 2022. CSIR Strategic Communications. Available online: https://www.csir.co.za/csir-releases-statistics-on-power-generation-south-africa-2022#:~:text=Coal%20still%20dominates%20the%20South,of%20the%20total%20energy%20mix (accessed on 16 June 2023).
10. Zheng, X.; Streimikiene, D.; Balezentis, T.; Mardani, A.; Cavallaro, F.; Liao, H. A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. *J. Clean. Prod.* **2019**, *234*, 1113–1133. [CrossRef]
11. Friedrich, J.; Ge, M.; Pickens, A.; Vigna, L. This interactive chart shows changes in the world's top 10 emitters. *World Resour. Inst.* **2020**, *10*, 1–5.
12. Olivier, J.G.; Schure, K.; Peters, J. Trends in global CO_2 and total greenhouse gas emissions. *PBL Neth. Environ. Assess. Agency* **2017**, *5*, 1–11.
13. Kumar, A.; Singh, P.; Raizada, P.; Hussain, C.M. Impact of COVID-19 on greenhouse gases emissions: A critical review. *Sci. Total Environ.* **2022**, *806*, 150349–150359. [CrossRef] [PubMed]
14. Ibrahim, I.D.; Hamam, Y.; Alayli, Y.; Jamiru, T.; Sadiku, E.R.; Kupolati, W.K.; Ndambuki, J.M.; Eze, A.A. A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. *Energy Strategy Rev.* **2021**, *38*, 100740. [CrossRef]
15. Longe, O.M.; Myeni, L.; Ouahada, K. Renewable energy solution for electricity access in rural South Africa. In Proceedings of the 2019 IEEE International Smart Cities Conference (ISC2), Casablanca, Morocco, 14–17 October 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 772–776.
16. Aliyu, A.K.; Modu, B.; Tan, C.W. A review of renewable energy development in Africa: A focus in South Africa, Egypt and Nigeria. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2502–2518. [CrossRef]

17. Udeagha, M.C.; Ngepah, N. Disaggregating the environmental effects of renewable and non-renewable energy consumption in South Africa: Fresh evidence from the novel dynamic ARDL simulations approach. *Econ. Chang. Restruct.* **2022**, *55*, 1767–1814. [CrossRef]
18. Adedoyin, F.F.; Ozturk, I.; Agboola, M.O.; Agboola, P.O.; Bekun, F.V. The implications of renewable and non-renewable energy generating in Sub-Saharan Africa: The role of economic policy uncertainties. *Energy Policy* **2021**, *150*, 112115–112127. [CrossRef]
19. Ozcan, B.; Ozturk, I. Renewable energy consumption-economic growth nexus in emerging countries: A bootstrap panel causality test. *Renew. Sustain. Energy Rev.* **2019**, *104*, 30–37. [CrossRef]
20. Armeanu, D.S.; Joldes, C.C.; Gherghina, S.C.; Andrei, J.V. Understanding the multidimensional linkages among renewable energy, pollution, economic growth and urbanization in contemporary economies: Quantitative assessments across different income countries' groups. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110818–110839. [CrossRef]
21. Nawaz, M.A.; Hussain, M.S.; Kamran, H.W.; Ehsanullah, S.; Maheen, R.; Shair, F. Trilemma association of energy consumption, carbon emission, and economic growth of BRICS and OECD regions: Quantile regression estimation. *Environ. Sci. Pollut. Res.* **2021**, *28*, 16014–16028. [CrossRef]
22. Agyeman, F.O.; Ma, Z.; Li, M.; Sampene, A.K.; Dapaah, M.F.; Kedjanyi, E.A.G.; Buabeng, P.; Li, Y.; Hakro, S.; Heydari, M. Probing the effect of governance of tourism development, economic growth, and foreign direct investment on carbon dioxide emissions in Africa: The African experience. *Energies* **2022**, *15*, 4530. [CrossRef]
23. Du, L.; Wei, C.; Cai, S. Economic development and carbon dioxide emissions in China: Provincial panel data analysis. *China Econ. Rev.* **2012**, *23*, 371–384. [CrossRef]
24. Salahuddin, M.; Gow, J.; Ozturk, I. Is the long-run relationship between economic growth, electricity consumption, carbon dioxide emissions and financial development in Gulf Cooperation Council Countries robust? *Renew. Sustain. Energy Rev.* **2015**, *51*, 317–326. [CrossRef]
25. Sufyanullah, K.; Ahmad, K.A.; Ali, M.A.S. Does emission of carbon dioxide is impacted by urbanization? An empirical study of urbanization, energy consumption, economic growth and carbon emissions-Using ARDL bound testing approach. *Energy Policy* **2022**, *164*, 112908–112925. [CrossRef]
26. Info, K.C.; Today in Kimberly's History. Kimberly City Info, Kimberly. Available online: https://www.kimberley.org.za/2-september-today-in-kimberleys-history/ (accessed on 5 July 2023).
27. Buraimoh, E.; Adebiyi, A.A.; Ayamolowo, O.J.; Davidson, I.E. South Africa electricity supply system: The past, present and the future. In Proceedings of the 2020 IEEE PES/IAS PowerAfrica, Nairobi, Kenya, 25–28 August 2020; pp. 1–5.
28. Marais, L.; Cloete, J.; Lenka, M. The plight of mining cities in South Africa: Planning for growth and closure. *Cities* **2022**, *130*, 103965. [CrossRef]
29. Todes, A.; Turok, I. Spatial inequalities and policies in South Africa: Place-based or people-centred? *Prog. Plan.* **2018**, *123*, 1–31. [CrossRef]
30. Christie, R. The Creation of a Monopoly: The Victoria Falls and Transvaal Power Company Limited, 1905–1914. In *Electricity, Industry and Class in South Africa*; Springer: Berlin/Heidelberg, Germany, 1984; pp. 27–49.
31. ESKOM. Empowering the Future Together. Available online: https://www.eskom.co.za/heritage/ (accessed on 5 July 2023).
32. Eskom. The History of the Sabie Gorge and Malieveld Hydro-Electric Power Stations. Available online: https://sabie.co.za/blog/?p=1849 (accessed on 5 July 2023).
33. Eskom. The Years of Expansion and Change. Available online: https://www.eskom.co.za/heritage/history-in-decades/eskom-1983-1992/ (accessed on 5 July 2023).
34. Molepo, J. Blackout: The Eskom Crisis, James-Brent Styan. *J. Public Adm.* **2018**, *53*, 795–798.
35. McGregor, L.; Nuttal, S. *Load Shedding: Writing on and over the Edge of South Africa*; Jonathan Ball Publishers: Johannesburg, South Africa, 2013.
36. Guardian. Power Plant Blast Threatens Supply. Available online: https://mg.co.za/article/2011-03-18-power-plant-blast-threatens-supply/ (accessed on 5 July 2023).
37. Energy. Lethabo Power Station Out of Action. Available online: https://www.bizcommunity.com/Article/196/693/182965.html (accessed on 5 July 2023).
38. Daily Investor. Medupi Unit 4 Explosion Repair Update. Available online: https://dailyinvestor.com/south-africa/10957/medupi-unit-4-explosion-repair-update/#:~:text=Unit%204%20of%20Eskom%E2%80%99s%20Medupi,service%20on%2031%20August%202024 (accessed on 5 July 2023).
39. Bloomberg. South African Power-Plant Breakdowns Hit a 2022 High. Bloomberg. Available online: https://www.bloomberg.com/news/articles/2022-12-07/south-african-power-plant-breakdowns-are-at-2022-high (accessed on 5 July 2023).
40. USAID. South Africa Energy Sector Overview. Available online: https://www.usaid.gov/powerafrica/south-africa#:~:text=According%20to%20the%20Ministry%20of,(MW)%20from%20all%20sources (accessed on 5 July 2023).
41. Macrotrends. South Africa Population 1950–2023. Available online: https://www.macrotrends.net/countries/ZAF/south-africa/population#:~:text=The%20current%20population%20of%20South,a%201%25%20increase%20from%202020 (accessed on 5 July 2023).
42. CEIC Data. South Africa National Government Debt. Available online: https://www.ceicdata.com/en/indicator/south-africa/national-government-debt#:~:text=in%20Apr%202023?-,South%20Africa%20National%20Government%20Debt%20reached%20263.9%20USD%20bn%20in,table%20below%20for%20more%20data (accessed on 5 July 2023).

43. Eberhard, A.; Shkaratan, M. Powering Africa: Meeting the financing and reform challenges. *Energy Policy* **2012**, *42*, 9–18. [CrossRef]
44. NERC. NESI Generation Statistics. Available online: https://nerc.gov.ng/resources/nesi-generation-statistics/ (accessed on 5 July 2023).
45. GlobalData. Egypt Power Market Size and Trend. Available online: https://www.globaldata.com/store/report/egypt-power-market-analysis/ (accessed on 5 July 2023).
46. Data. Egypt Population Trend. Available online: https://datacommons.org/place/country/EGY/?utm_medium=explore&mprop=count&popt=Person&hl=en (accessed on 5 July 2023).
47. DBSA. How Can We Reduce the Carbon Footprint in Africa. Available online: https://www.dbsa.org/article/how-can-we-reduce-carbon-footprint-africa#:~:text=South%20Africa%20has%20the%2014th,5%25%20rise%20in%20carbon%20emissions (accessed on 7 July 2023).
48. Bekun, F.V.; Emir, F.; Sarkodie, S.A. Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa. *Sci. Total Environ.* **2019**, *655*, 759–765. [CrossRef] [PubMed]
49. Narayan, P.K.; Narayan, S. Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. *Energy Policy* **2010**, *38*, 661–666. [CrossRef]
50. Our World in Data. South Africa: CO2 Country Profile. Available online: https://ourworldindata.org/co2/country/south-africa (accessed on 7 July 2023).
51. Njoh, A.J. Renewable energy as a determinant of inter-country differentials in CO_2 emissions in Africa. *Renew. Energy* **2021**, *172*, 1225–1232.
52. Walwyn, D.R.; Brent, A.C. Renewable energy gathers steam in South Africa. *Renew. Sustain. Energy Rev.* **2015**, *41*, 390–401. [CrossRef]
53. Belelie, M.D.; Burger, R.P.; Mkhatshwa, G.; Piketh, S.J. Assessing the impact of Eskom power plant emissions on ambient air quality over KwaZamokuhle. *Clean Air J.* **2019**, *29*, 29–37.
54. NREL. Life Cycle Assessment and Photovoltaic (PV) Recycling: Designing a More Sustainable Energy System. Available online: https://www.nrel.gov/state-local-tribal/blog/posts/life-cycle-assessment-and-photovoltaic-pv-recycling-designing-a-more-sustainable-energy-system.html (accessed on 7 July 2023).
55. Singh, S.; Bhatti, T.; Kothari, D. A review of wind-resource-assessment technology. *J. Energy Eng.* **2006**, *132*, 8–14. [CrossRef]
56. Musango, J.K.; Amigun, B.; Brent, A.C. Sustainable electricity generation technologies in South Africa: Initiatives, challenges and policy implications. *Energy Environ. Res.* **2011**, *1*, 124. [CrossRef]
57. Diab, R.D. *Wind atlas of South Africa*; Department of Mineral and Energy Affairs: Pretoria, South Africa, 1995.
58. Szewczuk, S.; Prinsloo, F. Wind Atlas for South Africa (WASA): Project overview and current status. In Proceedings of the CSIR 3rd Biennial Conference: 2010 Science Real and, Relevant, CSIR International Convention Center, Pretoria, South Africa, 30 August–1 September 2010.
59. Wind Atlas for South Africa (WASA) SANEDI. Available online: http://www.wasaproject.info (accessed on 7 July 2023).
60. EnergyFact. 27MW Sustainable Wind Power Generated. Available online: https://rb.gy/xvtdn (accessed on 7 July 2023).
61. Jain, S.; Jain, P. The rise of renewable energy implementation in South Africa. *Energy Procedia* **2017**, *143*, 721–726. [CrossRef]
62. Wind Atlas for South Africa Launched. Available online: https://www.esi-africa.com/industry-sectors/generation/wind-atlas-for-south-africa-launched/ (accessed on 7 July 2023).
63. Department of Mineral Resources and Energy. Independent Power Producers Procurement Programme (IPPPP): An Overview. Available online: https://www.ipp-projects.co.za/Publications/GetPublicationFile?fileid=2d03d621-6dc4-ec11-956e-2c59e59ac9cd&fileName=20220318_IPP%20Office%20Q3%20Overview%202021-22%20WEB%20VERSION.PDF (accessed on 11 July 2023).
64. Karamanski, S.; Erfort, G. Wind Energy Supply Profiling and Offshore Potential in South Africa. *Energies* **2023**, *16*, 3668. [CrossRef]
65. Gandhar, S.; Ohri, J.; Singh, M. A critical review of wind energy based power generation systems. *Asian J. Water Environ. Pollut.* **2020**, *17*, 29–36. [CrossRef]
66. Emetere, M.; Akinyemi, M. Climate Variability and Renewable Energy Planning. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *331*, 012036. [CrossRef]
67. Sebestyén, V. Renewable and Sustainable Energy Reviews: Environmental impact networks of renewable energy power plants. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111626. [CrossRef]
68. Kunz, T.H.; Arnett, E.B.; Erickson, W.P.; Hoar, A.R.; Johnson, G.D.; Larkin, R.P.; Strickland, M.D.; Thresher, R.W.; Tuttle, M.D. Ecological impacts of wind energy development on bats: Questions, research needs, and hypotheses. *Front. Ecol. Environ.* **2007**, *5*, 315–324. [CrossRef]
69. Barré, K.; Le Viol, I.; Bas, Y.; Julliard, R.; Kerbiriou, C. Estimating habitat loss due to wind turbine avoidance by bats: Implications for European siting guidance. *Biol. Conserv.* **2018**, *226*, 205–214. [CrossRef]
70. Nazir, M.S.; Ali, N.; Bilal, M.; Iqbal, H.M. Potential environmental impacts of wind energy development: A global perspective. *Curr. Opin. Environ. Sci. Health* **2020**, *13*, 85–90. [CrossRef]
71. Kikuchi, R. Adverse impacts of wind power generation on collision behaviour of birds and anti-predator behaviour of squirrels. *J. Nat. Conserv.* **2008**, *16*, 44–55. [CrossRef]
72. Nonhebel, S. Renewable energy and food supply: Will there be enough land? *Renew. Sustain. Energy Rev.* **2005**, *9*, 191–201. [CrossRef]

73. Van de Ven, D.-J.; Capellan-Peréz, I.; Arto, I.; Cazcarro, I.; de Castro, C.; Patel, P.; Gonzalez-Eguino, M. The potential land requirements and related land use change emissions of solar energy. *Sci. Rep.* **2021**, *11*, 2907. [CrossRef] [PubMed]
74. Statista. Total Wind Energy Capacity in South Africa from 2013 to 2023. Available online: https://www.statista.com/statistics/1218114/south-africa-total-wind-energy-capacity/ (accessed on 24 June 2024).
75. Hernández-Callejo, L.; Gallardo-Saavedra, S.; Alonso-Gómez, V. A review of photovoltaic systems: Design, operation and maintenance. *Sol. Energy* **2019**, *188*, 426–440. [CrossRef]
76. Oliveira-Pinto, S.; Stokkermans, J. Assessment of the potential of different floating solar technologies–Overview and analysis of different case studies. *Energy Convers. Manag.* **2020**, *211*, 112747. [CrossRef]
77. Wang, P.; Yang, N.; Xie, L.; Xu, Y.; He, H.; Fu, Y.; Shen, X. Theoretical Analysis of InGaN Solar Energy Converters Based on Photon-Enhanced Thermionic Emission. *Energies* **2023**, *16*, 3483. [CrossRef]
78. Qiu, H.; Xu, H.; Ni, M.; Xiao, G. Photo-thermo-electric modeling of photon-enhanced thermionic emission with concentrated solar power. *Sol. Energy Mater. Sol. Cells* **2022**, *246*, 111922. [CrossRef]
79. Daniela-Abigail, H.-L.; Tariq, R.; El Mekaoui, A.; Bassam, A.; De Lille, M.V.; Ricalde, L.J.; Riech, I. Does recycling solar panels make this renewable resource sustainable? Evidence supported by environmental, economic, and social dimensions. *Sustain. Cities Soc.* **2022**, *77*, 103539. [CrossRef]
80. Hosseini, S.E. An outlook on the global development of renewable and sustainable energy at the time of COVID-19. *Energy Res. Soc. Sci.* **2020**, *68*, 101633. [CrossRef]
81. Ajayan, J.; Nirmal, D.; Mohankumar, P.; Saravanan, M.; Jagadesh, M.; Arivazhagan, L. A review of photovoltaic performance of organic/inorganic solar cells for future renewable and sustainable energy technologies. *Superlattices Microstruct.* **2020**, *143*, 106549. [CrossRef]
82. Hosenuzzaman, M.; Rahim, N.A.; Selvaraj, J.; Hasanuzzaman, M.; Malek, A.A.; Nahar, A. Global prospects; progress, policies, and environmental impact of solar photovoltaic power generation. *Renew. Sustain. Energy Rev.* **2015**, *41*, 284–297. [CrossRef]
83. Tawalbeh, M.; Al-Othman, A.; Kafiah, F.; Abdelsalam, E.; Almomani, F.; Alkasrawi, M. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. *Sci. Total Environ.* **2021**, *759*, 143528. [CrossRef] [PubMed]
84. Mustafa, R.J.; Gomaa, M.R.; Al-Dhaifallah, M.; Rezk, H. Environmental impacts on the performance of solar photovoltaic systems. *Sustainability* **2020**, *12*, 608. [CrossRef]
85. Xu, Z.; Li, Y.; Gao, G.; Xie, F.; Ju, R.; Yu, S.; Liu, K.; Li, J.; Wang, W.; Li, W.; et al. Scalable selective absorber with quasiperiodic nanostructure for low-grade solar energy harvesting. *APL Photonics* **2023**, *8*, 020801. [CrossRef]
86. Divya, A.; Adish, T.; Kaustubh, P.; Zade, P. Review on recycling of solar modules/panels. *Sol. Energy Mater. Sol. Cells* **2023**, *253*, 112151. [CrossRef]
87. Sharma, V.; Aziz, S.M.; Haque, M.H.; Kauschke, T. Effects of high solar photovoltaic penetration on distribution feeders and the economic impact. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110021. [CrossRef]
88. Maka, A.O.; Alabid, J.M. Solar energy technology and its roles in sustainable development. *Clean Energy* **2022**, *6*, 476–483. [CrossRef]
89. Naicker, P.; Thopil, G.A. A framework for sustainable utility scale renewable energy selection in South Africa. *J. Clean. Prod.* **2019**, *224*, 637–650. [CrossRef]
90. Ayamolowo, O.J.; Manditereza, P.; Kusakana, K. South Africa power reforms: The Path to a dominant renewable energy-sourced grid. *Energy Rep.* **2022**, *8*, 1208–1215. [CrossRef]
91. Statista. Total Solar Energy Capacity in South Africa from 2013 to 2023. Available online: https://www.statista.com/statistics/1218115/south-africa-total-solar-energy-capacity/#:~:text=Total%20solar%20energy%20capacity%20in%20South%20Africa%202013-2023&text=During%20the%20period%20under%20review,an%20alternative%20source%20of%20electricity (accessed on 24 June 2024).
92. Umoh, V.; Davidson, I.; Adebiyi, A.; Ekpe, U. Methods and Tools for PV and EV Hosting Capacity Determination in Low Voltage Distribution Networks—A Review. *Energies* **2023**, *16*, 3609. [CrossRef]
93. Umoh, V.; Adebiyi, A.; Moloi, K. Hosting Capacity Assessment of South African Residential Low-Voltage Networks for Electric Vehicle Charging. *Eng* **2023**, *4*, 1965–1980. [CrossRef]
94. Moyo, A. New Portal Displays SA's Solar Installation Data. IT Web, 6 October 2023. Available online: https://www.itweb.co.za/article/new-portal-displays-sas-solar-installation-data/DZQ58MV8eDxvzXy2 (accessed on 29 February 2024).
95. 15 Biggest Solar Projects in South Africa. Solar Feeds. Available online: https://www.solarfeeds.com/mag/biggest-solar-projects-in-south-africa/ (accessed on 4 March 2024).
96. Weekly Data: South Africa's Unprecedented Rooftop Solar Boom. Energy Monitor. Available online: https://rb.gy/lv0yzp (accessed on 4 March 2024).
97. Rao, N.D.; Min, J.; Mastrucci, A. Energy requirements for decent living in India, Brazil and South Africa. *Nat. Energy* **2019**, *4*, 1025–1032. [CrossRef]
98. Tang, A.; Alsultany, F.H.; Borisov, V.; Mohebihafshejani, A.; Goli, A.; Mostafaeipour, A.; Riahi, R. Technical, environmental and ranking analysis of using solar heating: A case study in South Africa. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102299. [CrossRef]
99. Adebiyi, A.A.; Lazarus, I.J.; Saha, A.K.; Ojo, E.E. Performance analysis of 8 kW Grid-tied solar photovoltaic power plant in Durban South Africa. *Int. J. Mech. Eng. Technol.* **2019**, *10*, 82–95. [CrossRef]

100. Redstone Key Facts. SR Energy. Available online: https://sr.energy/redstone/ (accessed on 4 March 2024).
101. Zhang, H.; Baeyens, J.; Degrève, J.; Cacères, G. Concentrated solar power plants: Review and design methodology. *Renew. Sustain. Energy Rev.* **2013**, *22*, 466–481. [CrossRef]
102. Shahabuddin, M.; Alim, M.A.; Alam, T.; Mofijur, M.; Ahmed, S.F.; Perkins, G. A critical review on the development and challenges of concentrated solar power technologies. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101434. [CrossRef]
103. Pavlović, T.M.; Radonjić, I.S.; Milosavljević, D.D.; Pantić, L.S. A review of concentrating solar power plants in the world and their potential use in Serbia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3891–3902. [CrossRef]
104. Hafez, A.; Soliman, A.; El-Metwally, K.; Ismail, I. Solar parabolic dish Stirling engine system design, simulation, and thermal analysis. *Energy Convers. Manag.* **2016**, *126*, 60–75. [CrossRef]
105. Sonawane, P.D.; Raja, V.B. An overview of concentrated solar energy and its applications. *Int. J. Ambient Energy* **2018**, *39*, 898–903. [CrossRef]
106. Poullikkas, A.; Kourtis, G.; Hadjipaschalis, I. Parametric analysis for the installation of solar dish technologies in Mediterranean regions. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2772–2783. [CrossRef]
107. Cheng, Z.-D.; Leng, Y.-K.; Men, J.-J.; He, Y.-L. Numerical study on a novel parabolic trough solar receiver-reactor and a new control strategy for continuous and efficient hydrogen production. *Appl. Energy* **2020**, *261*, 114–136. [CrossRef]
108. Wang, Q.; Pei, G.; Yang, H. Techno-economic assessment of performance-enhanced parabolic trough receiver in concentrated solar power plants. *Renew. Energy* **2021**, *167*, 629–643. [CrossRef]
109. Price, H.; Beltran, J.; Ramirez, R. Advances in parabolic trough solar power technology. *J. Sol. Energy Eng.* **2002**, *124*, 109–125. [CrossRef]
110. Department of Energy. *State of Renewable Energy in South Africa*; Department of Energy: Pretoria, South Africa, 2015.
111. Miller, J. Promoting Sustainable Development in South Africa: Environmental Regulation in Support of Renewable Energy. Master's Thesis, University of the Western Cape, Cape Town, South Africa, 2016.
112. Baker, L. Commercial-scale renewable energy in South Africa and its progress to date. In *Green Power for Africa: Overcoming the Main Constraints*; Pueyo, A., Bawakyillenuo, S., Eds.; IDS Bulletin: Brighton, UK, 2017; Volume 48.
113. Fluri, T.P. The potential of concentrating solar power in South Africa. *Energy Policy* **2009**, *37*, 5075–5080. [CrossRef]
114. Wang, Z. *Design of Solar Thermal Power Plants*; Academic Press: Cambridge, MA, USA, 2019; pp. 1–46.
115. Weinstein, L.A.; Loomis, J.; Bhatia, B.; Bierman, D.M.; Wang, E.N.; Chen, G. Concentrating solar power. *Chem. Rev.* **2015**, *115*, 12797–12838. [CrossRef] [PubMed]
116. Ummadisingu, A.; Soni, M. Concentrating solar power–technology, potential and policy in India. *Renew. Sustain. Energy Rev.* **2011**, *15*, 5169–5175. [CrossRef]
117. Achkari, O.; El Fadar, A. Latest developments on TES and CSP technologies–Energy and environmental issues, applications and research trends. *Appl. Therm. Eng.* **2020**, *167*, 114–136. [CrossRef]
118. Morningstar, W. *The Physics of Solar Concentration*; Stanford University: Stanford, CA, USA, 2017.
119. Shafiullah, M.; Ahmed, S.D.; Al-Sulaiman, F.A. Grid integration challenges and solution strategies for solar PV systems: A review. *IEEE Access* **2022**, *10*, 52233–52257. [CrossRef]
120. Khodayar, M.E.; Feizi, M.R.; Vafamehr, A. Solar photovoltaic generation: Benefits and operation challenges in distribution networks. *Electr. J.* **2019**, *32*, 50–57. [CrossRef]
121. Prăvălie, R.; Patriche, C.; Bandoc, G. Spatial assessment of solar energy potential at global scale. A geographical approach. *J. Clean. Prod.* **2019**, *209*, 692–721. [CrossRef]