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Review

"Towards Sustainable Development: Analyzing the Viability and Integration of Renewable Energy Solutions in South Africa"—A Review

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Abstract: The global economy faces increasing environmental challenges and economic instability, prompting the adoption of innovative energy technologies as a crucial strategy. This study addresses the urgent quest for sustainable development in South Africa, specifically by evaluating renewable energy solutions. This study utilizes a comprehensive literature analysis to examine the current state of renewable energy infrastructure, policy frameworks, technological advancements, and economic viability within the South African context. Synthesizing insights from the existing literature on the interplay between energy, economy, and technology, this study aims to provide a refined understanding of renewable energy solutions' feasibility and integration potential. The exploration of these solutions in South Africa identifies key opportunities, challenges, and implications for sustainable development. These findings offer valuable guidance for policymakers, researchers, and stakeholders in advancing a country's transition towards a sustainable energy future.

Keywords: sustainable development; renewable energy; energy transition

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1. Introduction

Sustainable development has become an increasingly important problem over the past few years as the globe faces severe environmental and economic concerns. An essential component of sustainable development is developing and implementing innovative energy technologies that may effectively reduce carbon emissions and boost energy efficiency. Nevertheless, before new energy technologies can be widely used, they must undergo feasibility studies and optimization to ensure they are economically, ecologically, and socially feasible.

Many studies have explored and reviewed the potential of renewable energy in Africa. A recent study states that renewable energy is a significant driver of economic growth in African countries, particularly in Eastern and Central Africa [1]. Another study projected future energy demand and emissions, highlighting the potential for renewable energy to promote universal energy access and mitigate climate change, particularly in Africa [2]. Many researchers have concluded that renewable energy presents opportunities for Africa to achieve full electricity access in an economically, environmentally, and socially sustainable manner [2–4]. Therefore, renewable energy technologies are suitable for meeting the energy needs of Africa's urban and rural poor.

The electricity supply in different regions of Africa can be categorized into three main types: gas-based, hydro-based, and coal-based, as shown in Figure 1. In North and West Africa, electricity supply is primarily driven by gas, with Egypt, Algeria, and Nigeria being the major contributors. However, East and Central Africa rely heavily on hydropower as the primary source of electricity, with the Democratic Republic of Congo, Ethiopia, and Uganda being the leading producers. In Southern Africa, coal dominates the electricity supply, more than 70%, with the Republic of South Africa being the major contributor. This article

will review and aim to offer a comprehensive overview of the current state of knowledge on the topic under study, gathering and integrating relevant empirical information from previous studies. By reviewing the existing literature, the following sections will give an in-depth overview of the potential for renewable energy development in South Africa, including current infrastructure, policies and regulations, technological advancements, and economic feasibility.

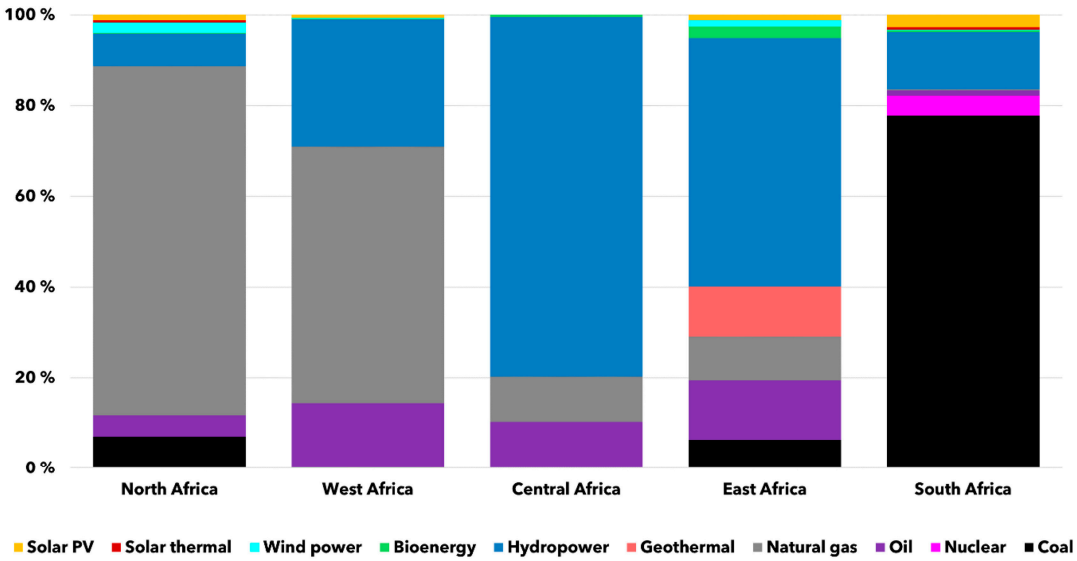

Figure 1. Africa's electricity supply mix by power pool in 2020, extracted from [5].

2. Overview of the Energy Situation in South Africa

According to the World Bank, South Africa has the highest energy demand in Africa and is one of the largest electricity producers in the world [6]. Despite its vast natural resources, South Africa faces severe challenges to sustainable development in the energy sector. According to Solomon et al. [7], South Africa faces an erratic power supply, resulting in persistent load shedding owing to the aging of most coal-fired power plants. Load shedding is a technique employed during periods of high electrical demand to reduce the burden of intermittent loads and maintain the operational stability of the power grid [8]. This momentarily decreases the power usage of the designated consumers to achieve equilibrium between the power taken in and generated in the primary system.

The demand for electricity in South Africa is increasing by about 4% annually, driven by industrial and economic growth [9]. The South African government requires a stable electrification program to meet this demand. As illustrated below, coal has maintained its status as a primary energy source owing to its widespread availability and cost-effectiveness.

As of March 2020, more than 85% of electricity in South Africa was generated from fossil fuels [10]. As previously mentioned, in 2016, coal, serving as the primary energy source, was complemented by various other sources, such as nuclear, crude oil, natural gas, renewables, and waste energy, contributing significantly to the country's energy mix (See Figure 2). South Africa's population growth has led to an increased demand for energy. Therefore, the Department of Energy is implementing policies to ensure energy security by maintaining a steady supply. Additionally, the department is working towards providing universal access to energy by supplying power to everyone in the country, regardless of their geography or economic condition. The South African energy landscape is dominated by coal-fired power stations owned and run by Eskom, the state-owned power provider [7]. These power plants use coal of various grades to create and distribute power to different parts of the country. The published data from 2016 highlights that Eskom's production mix comprises 14 coal-fired power units, providing over 70% of the country's electrical output [10].

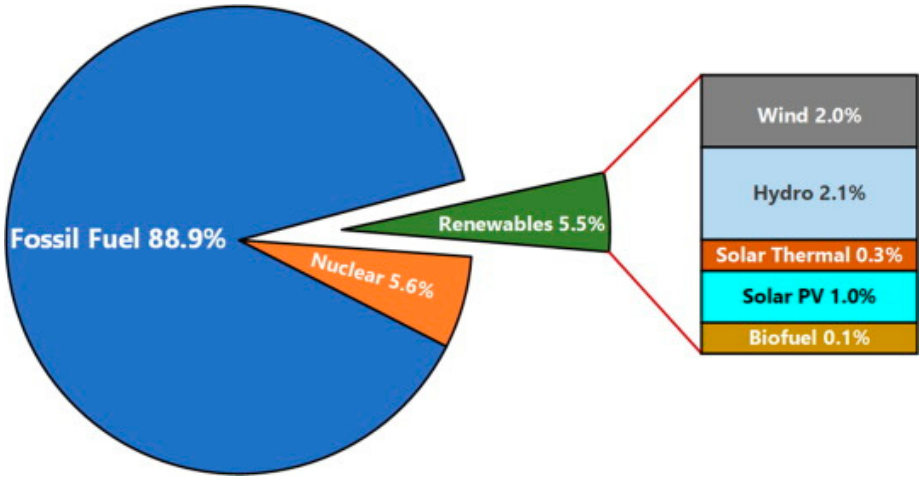

Figure 2. The Energy mix in South Africa, extracted from [10].

Despite being the world's 7th largest coal producer and relying heavily on it for power, South Africa is facing an energy crisis in the form of electricity shortages and blackouts. This dependence on coal worsens the crisis and harms the environment with substantial carbon emissions. However, South Africa has great potential for renewable energy technologies; therefore, to deal with the energy crisis in the country, the government adopted various policies to enable renewable energy generation in the energy mix. To adequately address and explain the issue of policies, Jain et al. [11] studied the implementation and adoption of sustainable energy sources in South Africa, providing information about potential renewable power supply and development in the nation at large by examining projects and policies established by the government and energy regulators. The authors highlighted the benefits of implementing renewable energy, such as job creation, foreign investment, and improved quality of life for local communities.

Furthermore, various African studies have suggested using cleaner, sustainable, and environmentally friendly energy sources, such as renewables, to reduce the environmental impact of energy production and modernize the energy industry [12]. In South Africa, several studies have investigated the relationship between energy consumption and economic growth [9,13]. In this context, feasibility analysis and optimization of new energy technologies for sustainable development in South Africa are crucial, thus analyzing the potential of integrating renewable energy sources into South Africa's electricity grid. Renewable energy projects must be evaluated for feasibility and optimized to maximize their potential performance while reducing costs and minimizing environmental impacts.

2.1. Energy Insights—South Africa

Most developing countries, such as South Africa, strive to develop their current energy sources further, and renewable energy sources have been established as a key priority area. Brent [14] argued that energy is critical for long-term development and prosperity; a country must adopt a multi-energy strategy and enhance the share of environmentally friendly and domestic energy sources. Energy efficiency measures are commonly considered a top priority in reducing carbon dioxide emissions and can give businesses a competitive advantage [15]. Despite this, nearly half of the cost-effective energy efficiency improvements proposed by industry are never adopted. Two researchers, T. Mezher and Tsai [16], proposed that developing countries suffer from energy shortages due to supply limitations and insufficient infrastructure, negatively impacting their economies.

Moreover, the practice of energy management can bolster a nation's energy security and catalyze the fostering of a competitive edge for industries. Additionally, the sustainable development model presented by the Department of Energy acquires around 40% of its potential carbon reduction from energy efficiency. Researchers have reviewed various aspects

concerning energy management and renewable energy in the past decades for feasibility and sustainable development [17]. Several elements that have attracted attention include:

- The significance of energy management and renewable energy;
- Sustainability of energy efficiency and new energy technologies;
- Green economy and financial aspects;
- Education about new energy technologies;
- Environmental and technological development;
- Government policies regarding energy development;
- Energy consumption review.

Industries, governments, and non-governmental organizations are all focusing on energy management since it may be a reasonably quick and cost-effective solution for businesses to save money and cut carbon emissions [18]. As a result, industrial energy management is primarily regarded as a critical component of worldwide efforts to combat climate change. Electricity demand in South Africa has been a topic of significant interest and research. Several papers have examined the relationship between population growth and electricity consumption to understand the problem at hand [19,20]. South Africa's electricity demand has surged due to production-related factors, with income being the primary determinant, which has been further affected by electricity price increases, prompting a shift towards renewable energy sources. According to the Southern African Power Pool, there is an anticipated rise in supply and demand for electricity, with an accompanying trend towards using renewable energy sources [21].

This aligns with L. Kitzing [22], who finds the same when evaluating that renewable energy can help people and communities escape poverty while reducing greenhouse gas emissions. The possible implications of renewable energy on poverty reduction are also explored in depth from three perspectives: socioeconomic, environmental, and renewable energy performance. Other studies indicated that renewable energy technologies are increasingly being utilized in South Africa, but there is still a gap since electricity demand has increased rapidly [9].

S. Khan et al. [23] highlighted that fossil fuels are being consumed at an alarming rate, and energy from renewable sources is the best possible substitute. The link between renewable energy usage and long-term economic development in emerging and developing economies has been evaluated [24]. The results show a positive correlation effect of renewable energy technologies on economic growth, resulting in a green economy for selected Asian and most African countries. The findings revealed a significant long-run link between renewable energy consumption and economic growth.

South Africa has been continuously impacted by ongoing concerns about the current state of its power systems, structures, and energy policy, which resulted in the 2007–2008 energy crisis and subsequent shortages throughout the next decade. South Africa's electrical "load shedding" in 2007/2008 was poorly prepared. It also points out that South Africa's economy has been harmed by chronic underinvestment in the country's energy industry, which has resulted in growing power prices and a scarcity of capacity during peak demand periods, leading to demand rationing [25,26].

The relationship between energy management and renewable energy versus unemployment has caused much ongoing debate around the globe, and South Africa is not an exception [27]. Bulavskaya et al. [28] examined the impact of renewable energy on job creation in the Netherlands using a neo-Keynesian CGEM Three-ME model. This detailed economic model examines the impact of energy policies on different parts of the economy, considering both direct and indirect effects, using the neo-Keynesian CGEM ThreeME to deduce the impact of moving to renewable energy systems in terms of key economic variables and the shift towards a renewable electricity mix in the Netherlands, highlighting a positive impact on the Dutch economy in terms of GDP, employment, investment, and other key economic variables.

Several studies have been conducted to identify the ideal balance between fossil fuels and renewable energy sources when assessing sustainability and feasibility [29]. The

feasibility analysis used the RETScreen modeling program [30]. This model compares the energy production of various clean and renewable technologies, considering life-cycle costs and reductions in greenhouse gas emissions (GHG). It also does a standardized and integrated financial, sensitivity, and risk analysis to establish the project's financial feasibility and risk.

According to the literature reviewed, renewable energy is the next promising energy source [31]. Solar energy has been pursued by developed countries such as Germany, the United States, and China. For developing countries, Temene et al. [25] discovered a long-run association between economic growth and renewable energy consumption.

Based on the literature reviewed above, the general goal of this study is to align and complement this research by looking at whether and how renewable energy technologies and energy management in the supply mix affect the South African economy. Finally, this research is unique in that it takes a holistic approach to renewable energy feasibility by combining an investigation of links between energy, the economy, and technology.

Based on the reviewed information, the following conclusions can be drawn:

1. Urgent need for renewable energy: the rapid consumption of fossil fuels necessitates transitioning towards renewable energy sources for sustainability.
2. Positive economic impact: studies suggest a positive correlation between renewable energy utilization and long-term economic growth in developing economies.
3. A strong link between renewable energy and growth: the findings reveal a significant long-term relationship between renewable energy consumption and economic development.

However, there is also a need to understand the following:

1. Individual country contexts and development trajectories;
2. Causality: establishing causal relationships beyond mere correlation;
3. Assessing the potential social impacts of renewable energy projects on communities and employment.

2.2. Government Policies Regarding Renewable Energy in South Africa

South Africa has a coal-driven energy sector. The state encounters significant energy-related challenges, primarily from inadequate infrastructure and the absence of suitable technologies to harness available energy resources effectively, particularly emerging renewable sources. Firstly, the white paper on Renewable Energy (1998–2003) was the government's overarching vision of the role of renewable energy within its energy economy, which entails fostering an environment in which modern renewable energy sources expand their share of the energy consumed. This ensures affordable and widespread access to electricity across South Africa, advancing sustainable development and environmental preservation goals.

According to the South African Constitution, the renewable energy policy of the South African white paper outlines the country's policy and regulatory framework for renewable energy [32]. The white paper on energy (1998) publication aimed to provide a coherent and insightful glimpse of the future of energy in South Africa [33]. The document was comprehensive and stated issues regarding using clean energy technologies and implementing renewable energy. The policy document pledged the government's support for developing, demonstrating, and implementing renewable energy sources for both small and medium industries. However, it did not clearly state the objectives and specific targets. Therefore, in 2003, the Department of Minerals and Energy released another white paper on renewable energy [34], focusing on long-term targets and specific objectives. The policy highlighted about 10,000 of GWh generation by 2013. The main benefits of the white paper were targeted at rural communities, those far away from the national grid, and those not connected, such as remote schools, rural clinics, and small factories.

The white paper emphasized promoting investment in South Africa's renewable energy sector while adhering to sustainable development principles [35]. In evaluating the white paper, a study by Mukonza et al. [36] explored South Africa's plans to boost wind energy for energy security and sustainable development. It evaluated the existing

policies, institutions, and programs to foster onshore wind energy adoption. This analysis demonstrated South Africa's effective establishment of essential policies, institutions, and programs to facilitate the growth of wind energy. A recent study noted a rise in renewable energy uptake in South Africa [11]. South Africa's energy policy, particularly in the context of the white paper, has been shaped by a range of factors. The country has made significant strides in energy efficiency, with a target of a 12% reduction in the national final energy demand by 2050 [36]. The promotion of renewable energy sources, such as wind power, is supported by a range of policies and institutions aimed at facilitating this transition. This initiative has gained momentum in recent years, and various measures have been implemented to encourage the adoption of sustainable energy alternatives. The uptake of wind energy is among the most viable and acceptable technologies in the renewable energy sector in South Africa [10,37]. Although South Africa has enacted policies and programs to support wind energy, implementation challenges and limitations persist. These hurdles may include funding constraints, community capacity for participation in wind projects, and the political prioritization of traditional fossil fuels over renewable energy sources.

Secondly, the Integrated Resource Plan (IRP) by the government seeks to improve and strengthen self-sufficient energy sources such as solar generation, self-generation, and co-generation, as outlined in the update document of the 2010 Integrated Resource Plan (IRP) [38]. This plan serves as a long-term blueprint for electricity generation and infrastructure in the country.

The initial Integrated Resource Plan (IRP) of South Africa refers to a comprehensive energy blueprint that outlines the country's long-term electricity generation and energy mix strategies [38]. This plan serves as a roadmap for meeting the nation's energy needs while considering factors such as sustainability, affordability, and security of supply. The IRP sets out the South African government's strategy for establishing new generation and transmission capacity for the country from 2010 to 2030.

The listed objectives of the IRP are to make electricity inexpensive, reduce greenhouse gas emissions, and reduce water usage. The government has developed a Renewable Energy Independent Power Producer Program (REIPPP) to attract more independent power producers (IPPs) to the renewable energy sector [39]. The REIPPP program, part of the energy mix outlined in the National Development Plan, aligns with the current South African policy that promotes renewable electricity generation [39]. The initiation of the REIPPP bidding process has expedited the widespread implementation of renewable energy projects.

Overall, South Africa has firmly committed to promoting renewable energy through various policies and initiatives. This commitment is driven by factors such as diversifying the energy mix away from coal, addressing climate change, and creating jobs. However, significant challenges remain in translating policies into concrete actions and achieving ambitious goals.

2.3. Discussion on the Review

The South African government has made significant strides in promoting renewable energy in its mix. The country has diverse renewable resources, including solar and wind power, which have been harnessed through various projects. The REIPPP has been a key driver in attracting private renewable energy investment. Renewable energy sources such as solar and wind power have been harnessed, decreasing the nation's dependence on conventional fossil fuels. Like many developing nations, South Africa struggles to meet its growing energy demands due to a surge in electricity needs driven by population growth, industrialization, and urbanization. The country has experienced periods of electricity shortages and load shedding, highlighting the need for increased energy capacity. Addressing these challenges is crucial for sustaining economic growth and ensuring a reliable energy supply.

South Africa's journey toward a more sustainable and diversified energy landscape is commendable. The emphasis on renewable energy sources is a positive step toward reduc-

ing environmental impacts and enhancing energy security. However, challenges persist, particularly in meeting growing energy demand and ensuring a stable supply. Continued investments in renewable energy projects and efforts to improve energy efficiency and grid infrastructure will be essential for South Africa to achieve a more sustainable and resilient energy future. Feasibility analysis and optimization are essential in deploying and adopting new energy technologies in South Africa. Feasibility analysis assesses the viability and potential of implementing these technologies, while optimization aims to enhance their performance and efficiency. Recent critical research on the feasibility analysis and optimization of an energy–water–heat nexus supplied by an autonomous hybrid renewable power generation system at airport facilities highlights the importance of sustainable energy access and water quality alternatives [40].

A more comprehensive description can be found in a recent study that discussed the state of renewable energy development in South Africa, and few studies have examined the technical feasibility of the large-scale integration of wind energy into the South African grid system [10]. The research discusses South Africa's electricity generation, biomass, wind, and solar energy industries and recommends steps for integrating renewable technologies. Several research papers have explored optimizing new energy technologies using different tools in South Africa. Optimization methods and software are crucial for sustainable energy system planning and forecasting, primarily promoting research on renewable energy production and consumption [41]. Goel et al. [42] presented an overview of various software tools available for designing and optimizing solar photovoltaic systems. The authors discussed various software tools for analyzing and optimizing renewable energy systems.

With a closer look at the literature on optimizing new energy technologies, Tozzi Jr. et al. [43] provide an overview of the various modeling tools used to simulate and optimize renewable energy projects by categorizing them into different project scales and comparing their similarities and differences. Data from several studies have identified HOMER and RETScreen as two popular software tools used to optimize and analyze renewable energy systems [44]. The researchers have proposed a modeling framework using HOMER and RETScreen to assess renewable energy systems, focusing on electricity generation. Many researchers have conclusively proved that policymakers, academic researchers, and energy planners use optimizing software tools such as HOMER Pro Version 3.16.2 and RETScreen Version 9.1 in the techno-economic design of renewable energy technologies for better decision making, to obtain better reliability and efficiency of power generation, and to save on installation costs [25,45–47].

Assessment of renewable energy systems combining techno-economic optimization with energy scenario analysis: Case studies have been conducted on optimizing new energy technologies in South Africa [48]. A recent study was conducted in South Africa by Leholo et al. [49]. They proposed a hybrid renewable energy plant methodology comprising a wind turbine, photovoltaic panels, and fuel cell for a remote GSM base station. The goal is to provide an alternative green energy source. The hybrid system and base station simulation results using the HOMER software revealed renewable energy solutions for air pollution reduction and remote off-grid load alternatives. The study concludes that the proposed hybrid renewable energy plant is feasible, with HOMER simulation results indicating its environmental friendliness and potential for implementation. A critical problem with this argument is that the simulation results produced by HOMER are based on the assumptions and inputs used in the software, which may not accurately reflect real-world conditions. This study suggests a hybrid renewable energy plant for air pollution reduction, and still, despite fewer emissions compared to fossil fuel-based systems, it is essential to assess the overall life cycle impact of the proposed hybrid system.

In South Africa, approximately 55% of rural people lack access to electricity [50]. New energy technologies can be utilized in South Africa to design microgrids by combining wind turbines, photovoltaic panels, and fuel cells for continuous power to off-grid loads. These microgrid designs have been argued to be a solution for rural areas in South Africa that lack access to electricity. This view is supported by Longe et al. [51], who proposed an optimized

renewable energy microgrid design using PV with a battery system as a better solution for electricity access in the rural areas of South Africa. This study compares the implementation of a renewable energy source microgrid in the Umhlabuyalingana Local Municipality, South Africa, providing a better solution to electricity access with grid extension. The system was simulated using HOMER, and the results favored photovoltaic and battery systems as the optimal combination, offering better electricity access in unelectrified areas. The conclusion is that a standalone microgrid is an optimal solution for providing electricity access to rural areas in South Africa.

3. Feasibility Analysis of New Energy Technologies in South Africa

This section introduces the concept of feasibility analysis in the context of energy technologies. This explains the purpose and significance of conducting feasibility studies to assess the technical, economic, environmental, and social aspects of implementing new energy technologies. The South African government is trying to promote renewable energy through various initiatives. Mukonza et al. [36] conducted a detailed examination to review policies, institutions, and programs to promote wind energy uptake and feasibility analysis in South Africa. The study concludes that South Africa has implemented critical policies, institutions, and programs for wind energy uptake.

A comparative study by Kumba et al. [3] found that renewable energy projects are feasible in South Africa, discussed the potential for renewable energy generation in the country, with a focus on solar and wind energy, and suggested that renewable energy implementation, particularly solar and wind energy, is feasible in South Africa. The country has immense potential for renewable energy generation with high levels of solar radiation and wind resources [10]. The government and energy regulators have developed policies and projects to promote the implementation of renewable energy in the country.

Diverse studies have examined Nigeria, South Africa, and Egypt, the top three largest economies in Africa, and have highlighted their significant renewable energy resources [52,53]. These studies have analyzed the feasibility and progress of adopting renewable energy in these countries and identified their challenges in developing their renewable energy sectors. According to these studies, South Africa has a high potential for renewable energy because of its abundant natural resources, such as solar, wind, and biomass. A more systematic and theoretical analysis by Ndlovu et al. [54] proved the feasibility of four primary renewable energy sources (hydro, solar, wind, and biomass) for uptake in South Africa. In a randomized controlled trial, the same researchers analyzed these cases. They suggested that with proper technology, awareness, and skills for harnessing resources, South Africa can overcome its persistent energy crisis by utilizing its naturally gifted renewable energy sources.

Many researchers have conducted additional studies to learn more about the fundamental viability of renewable energy in South Africa [55]. Numerous studies have been conducted to reveal and determine the feasibility of renewable energy in the country, and a recent survey by Oyewo et al. [19] proved that renewable energy in the country is possible. The study investigates pathways toward achieving the ambitious goal for South Africa to achieve 100% renewable electricity generation by the year 2050. The research serves as compelling evidence that, in the foreseeable mid-term future, adopting a renewable energy system is not only the most cost-effective choice but also the one with minor water requirements, minimal greenhouse gas emissions, and the potential to create a substantial number of jobs within the South African energy system. Overall, the feasibility of renewable energy in South Africa has been extensively studied with a focus on rural electrification, suggesting that renewable energy is a feasible and cost-effective option for meeting South Africa's energy needs, particularly in rural areas [19,50,56]. However, several limitations of this study must be considered.

A survey by An et al. [57] reveals several gaps and shortcomings in renewable energy policies and feasibility in South Africa, highlighting the limitations of renewable energy in South Africa, suggesting that imported crude oil is more practical for the needs of the

industries in South Africa. A systematic review by Batinge et al. [20] argues that there should be more research on renewable energy uptake in the sub-Sahara. The paper argues that the vastly underserved electricity market in sub-Saharan Africa presents a unique opportunity to transition from a fossil-intensive energy system to one centered around renewable resources. Furthermore, this underscores the need for additional research to delve deeper into this potential shift.

Despite some challenges, renewable energy is a feasible option for solving the energy crisis in South Africa. The primary limitations noted by energy researchers are concerns about poor infrastructure and delays in implementing renewable energy projects, including policy barriers that inhibit the feasibility of energy projects in South Africa, which can be addressed through effective policy-making and implementation [35,54,58]. Finally, it is also important to point out the argument that the feasibility of renewable energy projects makes it impossible to replace fossil fuels is mainly used by governments and fossil fuel companies to undermine investments in renewables.

3.1. New Energy Technologies in South Africa

As mentioned in the previous sections, South Africa's energy industry is dominated by coal. Various coal-fired power plants are at the end of their lifespans and may now be substituted with an energy mix combining and blending with renewable sources. Therefore, there is a need for further research on new energy technologies to solve the power crisis in South Africa. The optimization of new energy technologies in South Africa is an essential area of research and development, aiming to enhance the performance and efficiency of energy systems. According to the World Bank report [59], access to clean, modern energy is still a crisis in the sub-Sahara. There is still a need to optimize and implement new energy technologies to increase energy production for sustainable development. A recent study explored the potential for optimizing renewable energy technologies in South Africa [20]. It was revealed that renewable energy sources could meet approximately 30% of the country's power requirements.

According to the Energy Outlook [60], renewable energy technologies can enhance energy security by decreasing dependence on imported and fossil fuels and diversifying power supply in developing countries. In demonstrating the economic feasibility view, a study by Mudziwepasi et al. [50] investigated the viability of implementing household-sized renewable energy technologies, such as solar photovoltaic systems and wind generators, to provide electricity in remote rural areas of South Africa. It concluded that wind and solar energy are economically feasible in rural villages and remote regions of South Africa. Thus, the use of renewable energy in rural areas is feasible.

3.2. Limitation of the Development of Renewable Energy Sources in South Africa

Several factors limit the development of new energy technologies in South Africa as shown by Kumba et al. [3], who reviewed energy adoption in the country. The development of renewable energy sources in South Africa is hindered by various legal, policy, and economic barriers, as highlighted by Presley et al. [1]. This motion was supported by other researchers who concluded that factors like the dominance of fossil fuels, inadequate regulatory frameworks, and the high cost and risk structures of renewable energy technologies hinder the uptake of renewable energy sources. The region's low access to modern energy due to underprivileged energy policies, inadequate funding, and ineffective energy infrastructure further exacerbates the situation, which is crucial for the successful development of renewable energy sources in South Africa.

Additionally, the traditional method of expanding the grid does not effectively address energy poverty in rural areas, highlighting the need for off-grid solutions based on renewable energy sources [51]. There is also a need for a closer relationship between the government and the private sector to stimulate innovation and uptake in the renewable energy sector. However, many scholars argue that the significant barrier to renewable energy development in South Africa is the economics of renewable energy technologies,

such as cost and risk structures [61]. Another author argued that the significant problem with South Africa's renewable energy potential is restricted by government bureaucratic processes, low awareness, and high investment costs [7].

4. Optimization of Renewable Energy in South Africa

The optimization and optimal implementation of new energy technologies in South Africa is a critical area of research and development to enhance the performance and efficiency of energy systems. A closer look at the literature review in the South African energy area by scholars highlights the potential of renewable electricity sources to meet the energy needs of mining operations [35]. However, some argue that the previous literature suffers from specific weaknesses in demonstrating the feasibility of incorporating solar and wind power, reducing reliance on fossil fuels, and minimizing environmental impact [62]. Therefore, further research is required to fully understand the benefits of adopting renewable energy in the energy sector.

Optimization techniques and models have been used to optimize the unit commitment of electric power systems with intermittent renewable energy sources. The Southern African Development Community (SADC) region has implemented platforms, energy programs, and plans to address the energy crisis and improve efficiency within its member states [56]. Accordingly, the South African government has targeted generating 18 GW of renewable energy by 2030, focusing on optimizing renewable energy technologies [63].

A recent study by Wagh et al. [46] focused on solar energy optimization approaches and the problems and disadvantages within the energy area. The study also discusses the most current optimization techniques. The potential of renewable energy capacity has been explored in South Africa, and new energy technologies have provided opportunities to improve the economy.

Optimization models are commonly used in South Africa's electricity grid to determine the optimal deployment of renewable energy sources such as solar and wind energy. Previous studies have emphasized the importance of renewable energy optimization [11,64]. A considerable body of literature exists on optimization; for example, Siddaiah et al. [65] explored the feasibility and cost-effectiveness of hybrid renewable energy system-based power generation in off-grid applications, but it also delves into the optimization techniques used in the modeling of these systems. Additionally, the work explores using different research methods, such as reliability-based modeling, economic modeling, and optimization techniques, to investigate hybrid renewable energy systems.

Several studies have attempted to determine and implement an optimal ratio of wind power to solar power by considering different optimization targets [64]. The optimization of stand-alone and winding hybrid systems was reported by Al-Falahi et al. [66]. The review mentioned that classical algorithms, modern techniques, and software tools are among the most popular optimal sizing methodologies for complex optimization problems in renewable energy. The study evaluates standalone solar and wind energy systems, focusing on their economic, reliability, environmental, and social aspects, and provides insights into size optimization methodologies.

Asadi et al. [67] presented a comprehensive overview of biomass use. The article presents a stochastic analysis and proposes an optimized approach using a mixed-integer optimization model, thereby emphasizing the importance of optimizing the network to minimize the environmental impact, maximize economic efficiency, and meet customer demand. This paper discusses optimization methods for renewable and sustainable energy, including biomass supply chain design and strategic decision-making. Techniques such as stochastic programming and fuzzy programming can be used to address the uncertainty in biomass supply chain parameters.

Another optimization review was conducted by Momoh et al. [68] to understand and grasp the optimization techniques applied to the renewable energy resource optimization framework. A detailed examination by Kaufmann et al. [41] proved that optimization techniques are fundamental in planning, optimizing, and projecting sustainable renewable

energy systems. The research focused on optimization methods for their application in renewable energy production and consumption.

Nevertheless, the rapid expansion of renewable energy is yet to be coupled with a similar rise in the use of sustainable energy sources. Regarding the utilization of renewable energy, it is essential to note that previous research has primarily focused on optimizing the analysis of power systems that combine wind, hydro, thermal, and hydrothermal sources [7]. However, these findings might not directly apply to systems incorporating more intricate and diverse power sources. A recent study used the multi-objective optimization strategy of multi-source power system operation based on fuzzy chance constraint programming and an improved analytic hierarchy process [69]. The results from the optimization model proposed in the research enhance the economy, environmental protection, energy savings, and power system stability, leading to better utilization of renewable energy sources.

An ever-increasing body of literature shows that optimizing renewable energy has contributed to the uptake of renewable energy projects in rural areas, especially in Africa [61]. A detailed examination by Klepacka [70] emphasized the importance of renewable energy optimization in economic circumstances, the need to protect the natural environment, continuous education on technological advances, and the aim to strengthen self-reliance and independence in providing energy, especially in remote areas. The research highlighted the need for more investments in renewable energy to be extensively advocated, adopted, and endorsed by different countries, particularly in rural areas. This suggests that policy and financial support are crucial for optimizing the adoption and utilization of renewable energy sources.

Another study revealed that increasing economic activities in developing economies raise energy demand, mainly from conventional sources; therefore, more energy is needed by sourcing other energy alternatives [71]. In addition to these findings, the paper's results demonstrate that optimizing renewable energy increases economic output and reduces carbon dioxide emissions, contributing to the significance of renewable energy use. Optimizing renewable energy consumption contributes positively to economic output, indicating that promoting renewable energy generation and use can support sustainable economic development [72].

In addition to the above literature, researchers have noted that stochastic optimization methods and their applications in renewable energy systems are superior to deterministic methods in terms of social, technical, and economic aspects [73,74]. Overall, optimization techniques and models have been used to enhance the performance and efficiency of energy technologies. Several case studies and examples have explored the country's potential for various renewable energy technologies and the importance of optimization techniques in improving their performance and reducing costs [30,75,76].

5. Conclusions

In conclusion, the review of this article highlights the importance of feasibility analysis and optimization of new energy technologies for sustainable development in South Africa. This review reveals that various barriers still limit the adoption of renewable energy technologies. The findings indicate that the country faces significant challenges in meeting its growing energy demands while striving to achieve development goals. It is evident from the literature above that extensive studies have been conducted in the energy industry to inform the world about the transition from fossil fuels to new energy technologies, the feasibility and optimization of these technologies, and how to attain them. There is a global consensus on transitioning to more sustainable and cleaner energy sources and technologies.

The literature reviewed explores the feasibility analysis and optimization of new energy technologies for sustainable development in South Africa. The findings from this review also suggest that the energy policy and frameworks in South Africa, particularly

the IRP, promote renewable energy integration and expansion to address these challenges and drive sustainable development in South Africa.

Based on the literature examined and the review, the overall aim of this study was to complement the feasibility analysis and optimization of new energy technologies for sustainable development in South Africa. However, it is vital to acknowledge the challenges accompanying the implementation of new energy technologies in South Africa. Therefore, this article intends to fill this gap through the feasibility analysis conducted by the authors.

Common challenges faced by South Africa for the adoption of renewable energy:

1. High upfront costs: renewable energy technologies can be expensive to install compared with traditional fossil fuels.
2. Grid integration: integrating intermittent renewable sources, such as solar and wind, into the national grid requires additional infrastructure and management.
3. Job displacement: transitioning away from coal-based energy can lead to job losses in the sector, which requires reskilling and social support programs.
4. Policy uncertainty: unclear or unstable regulations discourage investment in new energy technologies.
5. Infrastructure limitations: South Africa's aging transmission and distribution infrastructure may not be sufficient to adopt new energy sources widely.
6. Social acceptance: concerns regarding land use, aesthetics, and potential environmental impacts can create resistance to specific technologies.

The primary objective of this article, as gleaned from the literature reviewed, is to evaluate and enhance the current research by investigating the impact of renewable energy technologies and energy management on the South African economy. This study stands out as it adopts a comprehensive approach to assessing renewable energy viability by exploring the interconnections between energy, the economy, and technology. Access to affordable and reliable energy is essential for economic growth and development, and technological innovation plays a key role in shaping the energy sector. The review highlights the main interconnections between energy and the economy. This article highlights that technological innovation is another vital factor in the energy-economy nexus. Therefore, the interconnections between energy, the economy, and technology are complex and multifaceted. Understanding these interconnections is essential for developing effective policies and strategies for transitioning to a more sustainable and equitable energy system in South Africa. It is essential to consider the potential impacts of energy policies on the economy and ensure that the benefits of energy transitions are equally shared.

The study also revealed that increasing economic activities in developing economies raise energy demand, mainly from conventional sources; therefore, more energy is needed by sourcing other energy alternatives to curb the demand [71]. Optimizing renewable energy consumption contributes positively to economic output, indicating that promoting renewable energy generation and use can support sustainable economic development.

To date, research has focused on the exploitation of renewable energy, which is vital for the world, since the world's energy use continues to rise because conventional energy sources are no longer adequate to meet energy demands, sparking an energy crisis [77]. The authors met the aim of optimizing renewable energy systems through the reviews, which combine multiple renewable energy sources as a promising solution to overcome the increasing energy demands.

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