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Review Article

Assessing the opportunities and obstacles of Africa's shift from fossil fuels to renewable sources in the southern region

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Abstract

This study presents a comprehensive analysis of the current energy landscape and the imperative transition toward renewable energy. It begins with an overview of current energy sources and trends, highlighting the disparity between supply and increasing demand. Adverse impacts of reliance on fossil fuels such as environmental degradation, economic volatility, and health hazards underscore the urgent need for a transition. The study then explores the vast potential of renewable energy sources (RES) such as solar, wind, hydrogen, and hydro, emphasizing their feasibility in the Southern African context. The positive impacts of integrating renewables are examined, including reduced greenhouse gas emissions, enhanced energy security, and economic diversification. Through case studies of regional examples, the success and failures of transitioning efforts are analyzed, providing valuable insights into best practices and pitfalls. The study identifies significant challenges in transitioning, particularly in grid-tied and off-grid scenarios, and discusses infrastructural, financial, and regulatory obstacles. The recommendations section outlines strategic steps for achieving a feasible transition, proposing either a full transition or specific percentages of renewable energy integration to meet energy demands. In conclusion, the study emphasizes the critical importance of adopting these strategies for sustainable development and global climate goals, advocating for continuous innovation and localized solutions to maximize the benefits of renewable energy. Key findings are that the environmental and economic effects of fossil fuel usage strain economies by increasing fossil fuel subsidies. RES are abundant in the Southern African region, and some projects have already been successfully implemented, especially in South Africa. Economic growth and technological advancement are some of the benefits of fully transitioning to renewables, but lack of skilled labor, infrastructure, necessary technology, and most importantly, high capital requirements, etc., are some challenges being faced. Hence, the need for regional cooperation, policy frameworks, and infrastructure enhancement, and investment mobilization for an accelerated transition.

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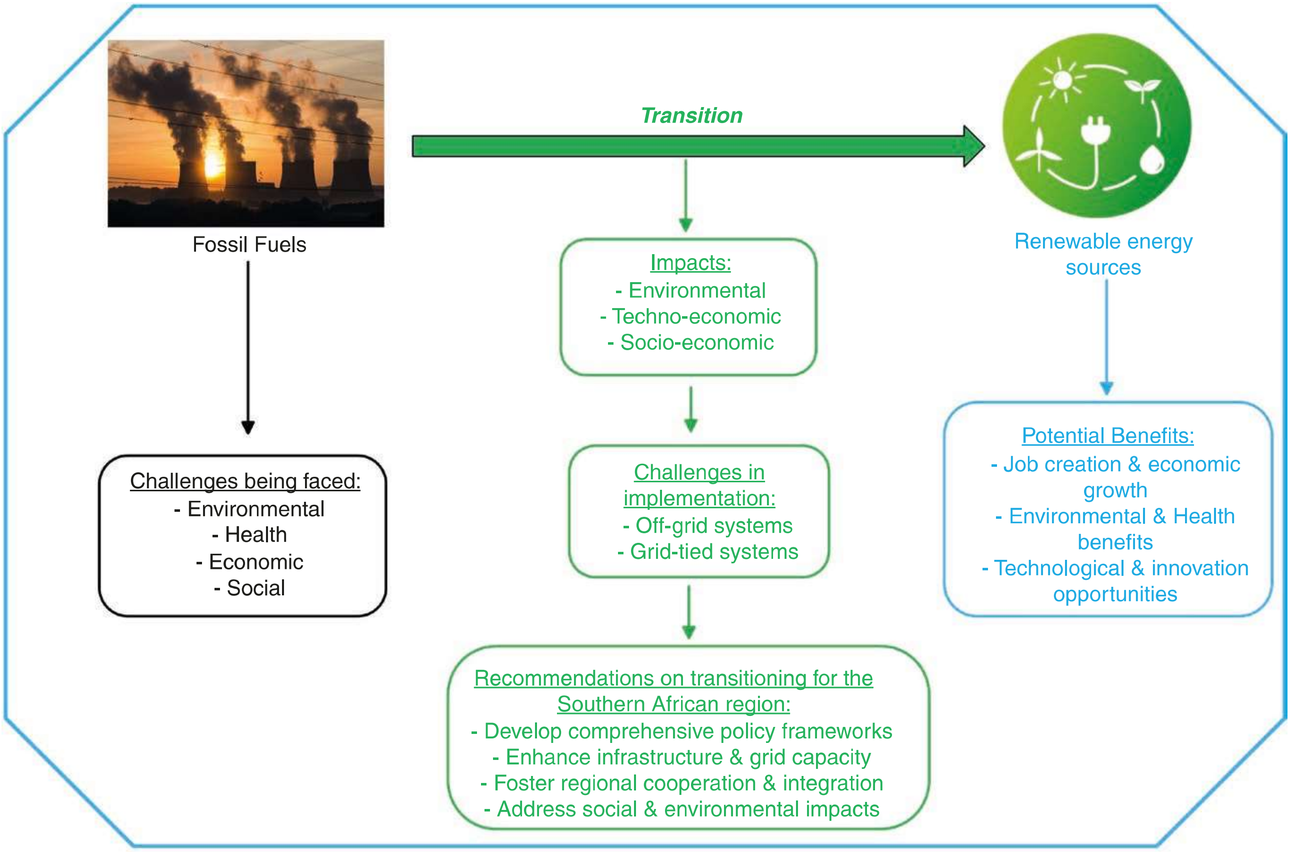
Graphical Abstract



Keywords: energy transition; fossil fuels; renewable energy; Southern Africa; sustainable development

1. Introduction

There are many concerns over the impacts of climate change across the globe, and there are equally emerging discussions about mitigating these impacts [1]. One such argument is the move from fossil fuels to renewable energy, which is gaining much attention in both developing and developed countries. Energy researchers are discussing more about renewable and sustainable energy because they are worried about the environment and the possibility that we will not have enough fossil energy in the future. Extensive research proved that Africa has a significant opportunity to lead this transition, given its abundant renewable energy resources [2].

This topic is significant due to a review by Kumba and Olanrewaju [3] showing that in the southern part of Africa, countries like South Africa, Zimbabwe, Botswana, and many others, have full potential for renewable energy with abundant renewable energy resources, including solar, wind, and hydropower, which present significant opportunities to transform its energy sector. The evidence so far points out that harnessing these resources can lead to improved energy security, economic growth, and public health outcomes. However, some researchers highlighted that the transition to renewable energy has some potential weaknesses especially the issue of funding [4].

Southern Africa's energy landscape is characterized by a heavy reliance on fossil fuels, particularly coal, which has traditionally been the backbone of power generation in countries like South Africa and Zimbabwe [5]. However, this dependency poses significant challenges, including high carbon emissions, environmental degradation, and vulnerability to global fossil fuel market fluctuations. Africa faces critical energy access issues, with nearly 60% of the rural population lacking reliable electricity [6], highlighting the urgent need for sustainable solutions. On the other hand, Southern Africa is endowed with abundant renewable energy resources, such as solar, wind, and hydropower, presenting vast opportunities for clean energy development [7]. According to [8], South Africa alone has the potential of generating more than 50 GW of wind energy, which could significantly reduce the current energy demands. However, transitioning to renewables requires overcoming obstacles such as inadequate infrastructure, limited financing, and policy challenges. Recent studies emphasize the importance of regional cooperation and investment in grid expansion to harness these renewable resources effectively, fostering economic growth and energy security [9].

Recent studies on renewable energy in Southern Africa highlight significant benefits [10, 11]. The adoption of renewable energy sources (RES) contributes to economic growth in the Southern African Power Pool [12]. The Southern African Development Community (SADC) region has abundant renewable resources, including hydro, solar, wind, and biomass however access to modern energy remains low [13]. Research gaps exist in the exploration of energy access across the region therefore there is a need for energy system modeling that integrates on- and off-grid solutions. There are key barriers to renewable energy adoption in Africa include socio-economic, technical, political, financial, and policy framework issues. To add to this perspective, the region faces substantial obstacles, including inadequate infrastructure, limited technical expertise, and financial constraints. In addition, the development of supportive policies and regulatory frameworks is essential for fostering investment and facilitating the integration of renewable energy technologies as being employed in different developed countries.

The current body of literature proved that as economies grow, the demand for electricity and modern energy services also increases, therefore putting additional pressure on existing energy systems that are often characterized by outdated old infrastructure and limited capacity [14]. These findings are consistent with the SADC report [15], which states that Southern Africa is experiencing rapid population growth and economic development, leading to a substantial increase in energy demand. The region's population is projected to double by 2050, meaning the need for reliable and affordable energy to support the growing urban centers and industrial activities.

However, many African countries still rely heavily on fossil fuels to meet their energy demands despite the urgent need to transition to renewable energy for sustainable development. Energy is seen as a driver for economic development in Africa, but there is a question of whether it can be done sustainably. In line with the Paris Agreement and the Sustainable Development Goals (SDGs), this article was inspired to address the issue of climate change using RES [16]. Africa has a vast amount of solar, wind, hydro, geothermal, and biomass resources, which makes it a place with great potential for renewable energy. It has become increasingly clear that RES can play a significant role in bringing electricity to many countries in the African region [2]. Research by Pacesila *et al.* [17] concluded that the developing countries in Europe have successfully made the transition to renewable energy, which raises the question of whether African countries can do the same. There is a strong correlation between energy and economic development, but many African countries face energy shortage issues that need to be addressed without harming the environment. A strong consensus in research proves that despite the challenges, transitioning to renewable energy in Africa has the potential to create jobs, reduce greenhouse gas emissions, and improve energy security [18, 19]. Africa is one of the continents that has relied on fossil fuels for power generation. However, due to the increasing pressure for a sustainable future according to the SDGs [20] and the increasing demand for power in Africa coupled with the issues of reducing climate problems, there is a need for countries to push for renewable energy resources. This section provides some evidence of the benefits of moving from fossil fuels to renewable energy.

The African Development Bank in 2020 revealed that starting in 2020 and going onwards, they will not be funding any coal projects, but the big 5 economies in Africa still rely heavily on fossil energy generation. The big question is: Can African countries move to renewable energy smoothly? Some reports have suggested that the transition from fossil fuels to renewable energy requires proper planning, and some industrial reports have revealed that transitioning from fossil fuels to renewable energy is neither easy nor simple [21]. Prior research suggests that there are many ongoing debates regarding the social and economic benefits of fossil fuels compared with RES [22].

In exploring the transition to renewable energy within Southern Africa, it is essential to consider the role of innovative financial mechanisms and technological advancements in driving sustainable development. Studies have shown that the synergy between green finance and high-tech innovation can significantly enhance regional sustainability, as evidenced by research on the Yangtze River Economic Belt, where both elements were found to be crucial for sustainable growth [23]. Additionally, digital finance has been identified as a key enabler of low-carbon productivity, with its effects observed through various transmission channels such as human capital and marketization, further emphasizing the importance of integrating advanced financial and technological solutions in the energy transition [24].

Despite the promising potential for renewable energy in Southern Africa, there is a significant gap in understanding the practical challenges and opportunities that the region faces in transitioning from fossil fuels to RES. While existing literature acknowledges the region's abundant renewable resources, there is a lack of comprehensive analysis on how these resources can be effectively harnessed amidst the infrastructural, financial, and policy-related obstacles. Therefore, the objective of this study is to explore the multifaceted energy evolution in Southern Africa by assessing both the opportunities presented by RES and the specific challenges that must be overcome to achieve a sustainable energy transition. This study aims to provide a detailed understanding of the region's energy future and offer actionable insights for policymakers and stakeholders working toward a resilient and sustainable energy system by analyzing the current impacts of fossil fuels and evaluating the potential of renewable energy.

2. Impacts of current energy sources

The global impacts of fossil fuels, including environmental degradation, health issues, and economic instability, are particularly pronounced in developing regions such as Southern Africa. Africa's energy sector is undergoing a major transformation as the region shifts toward sustainable energy sources and RES. As per SDG Goal 7 and the Paris Agreement, the objectives clearly state that an energy transition to sustainable energy sources is required by 2030 [20]. However, many researchers have noted that considerable planning is required.

Fossil fuels still supply about 80% of the world's energy needs; thus, oil, gas, and coal have played a dominant role in global energy systems for centuries now [22]. Their impact on the environment and the economies, their impact on health and the climate, necessitates a transition away from them. Fossil fuels have profound global effects, contributing significantly to climate change, air pollution, and health risks. They are the primary source of greenhouse gas emissions, driving climate change and causing severe environmental damage, such as air pollution and acid raids [25].

Fossil fuel combustion during the production of electricity poses different impacts. The impacts of current energy sources, particularly fossil fuels, in Southern Africa create a compelling case for transitioning to renewable energy. Understanding these impacts is crucial for assessing the opportunities and obstacles involved in this energy shift [2].

2.1 Environmental impacts

The use of fossil fuels has significant negative environmental impacts, including air pollution, global warming, and resource depletion [26]. Fossil fuels not only cause pollution and harm human health and the environment, but their extraction and exploitation also lead to significant environmental degradation. Additionally, the oil industry contributes to environmental issues like the intensification of the greenhouse effect, acid rain, and soil contamination, among others, highlighting the wide-ranging negative consequences of fossil fuel usage [27]. The combustion of fossil fuels is the largest source of greenhouse gas emissions, particularly carbon dioxide, which significantly contributes to global warming and climate change. The Intergovernmental Panel on Climate Change stated that fossil fuel usage accounts for about 89% of global emissions [28]. The use of fossil fuels impacts the environment by depleting natural resources [29]. Fossil fuel combustion releases a variety of pollutants, including sulfur dioxide, nitrogen oxides, particulate matter, and volatile organic compounds. These pollutants contribute to smog formation, acid rain, and respiratory diseases. The World Health Organization (WHO) reports that outdoor air pollution, largely driven by fossil fuel use, causes an estimated 4.2 million premature deaths annually [30]. However, the decrease in fossil fuel consumption during the coronavirus disease 2019 (COVID-19) pandemic has demonstrated positive environmental effects, such as reduced ozone formation and eutrophication, highlighting the advantages of decreased fossil fuel use. On the other hand, some argue that the reduction in fossil fuel consumption may have negative economic consequences, as it could lead to job losses in industries reliant on fossil fuels and slow down economic growth [31, 32]. Proponents of renewable energy argue that transitioning to clean energy sources can create new job opportunities and stimulate economic growth in the long run while reducing dependence on fossil fuels and mitigating their negative environmental impacts [33].

2.2 Health impacts

Many researchers discovered that the use of fossil fuels globally has profound health effects on children and adults alike [30]. It can be noted that fossil fuel-related air pollution and climate change significantly impact children's health, contributing to adverse birth outcomes, cognitive and behavioral problems, mental health disorders, asthma, immune system effects, and more. Thus, in summary, exposure to air pollutants from fossil fuel combustion is linked to a range of health issues [34]. The health impacts of fossil fuel pollution place a significant burden on public health systems and economies. A study by Fuller et al. [35] estimated that pollution-related diseases accounted for 16% of all deaths globally in 2015, with fossil fuel pollution being a major contributor. A global model study highlights that a phaseout of fossil fuel use could prevent millions of premature deaths annually, reduce climate cooling effects, increase rainfall in densely populated regions, and limit global warming, emphasizing the urgent need for emission reductions to safeguard public health and mitigate climate change impacts [36]. Additionally, reforming fossil fuel subsidies can lead to improved air quality, resulting in significant health benefits and potentially saving hundreds of thousands of lives by 2035. While reducing fossil fuel subsidies is a necessary step toward improving air quality, and it is important to note that this alone may not be enough. To add to this factors such as increased use of RES and stricter regulations on industrial emissions must also be considered to effectively address the issue of air pollution.

2.3 Economic and social impacts

The use of fossil fuels has significant negative impacts on both the environment and human health, leading to economic and social consequences [26]. These include air pollution, global warming, and resource depletion. The negative externalities of fossil fuel use, such as healthcare costs, environmental degradation, and climate change mitigation, impose substantial economic costs, straining economic budgets. The International Monetary Fund estimated that global fossil fuel subsidies, including externalities, amounted to $5.2 trillion in 2017, underscoring the need for economic reforms to address these hidden costs [37]. The transition to RES is seen as a solution to these issues by Kumba *et al.* [38], offering socio-economic advantages.

A discussion by Eisenack *et al.* [39] on fossil fuels suggests that dependence on fossil fuels only creates vulnerabilities in energy security and contributes to geopolitical tensions. Countries reliant on fossil fuel imports are subject to market volatility and supply disruptions, whereas major fossil fuel exporters face economic instability from fluctuating prices. Moreover, competition over fossil fuel resources has historically led to conflicts and political instability, and the extensive reliance on fossil fuels has facilitated global economic growth but at significant environmental, health, and economic costs.

2.4 Opportunities for transition to other sources

The literature underscores the urgent need to transition to sustainable energy sources to mitigate these adverse effects. Addressing the impact of fossil fuels requires coordinated global efforts, policy reforms, and investment in renewable energy technologies to achieve a sustainable and resilient future. The above literature provides a strong emphasis on the importance of transitioning to renewable energy, but this transition must be carefully managed to ensure energy security and economic stability. Coordinated global efforts, policy reforms, and investment in renewable energy technologies are crucial, but they must be balanced with the realities of current energy needs and the socio-economic benefits provided by fossil fuels. Many researchers argue that the transition to sustainable energy sources, while necessary to mitigate environmental, health, and economic costs, poses significant challenges, including the need for substantial investment, technological advancements, and the development of new infrastructure [33, 40].

The extensive reliance on fossil fuels has profound environmental, health, and economic impacts, particularly in developing regions like Southern Africa. Southern Africa faces both significant opportunities and substantial obstacles in its transition from fossil fuels to RES [14]. A publication by the International Renewable Energy Agency (IRENA) states that RES are abundant, particularly wind, solar, and others [41]. Nevertheless, the region also faces some challenges in terms of investments, capital, and infrastructure development for the adoption of these sources [7]. Therefore, leveraging its renewable energy potential and addressing the obstacles through coordinated efforts and investments, Southern Africa can achieve sustainable development and reduce its reliance on fossil fuels, contributing to global efforts to mitigate climate change.

2.5 Benefits of transition to other sources

2.5.1 *Job creation and economic growth*

Many researchers highlighted that the renewable energy sector could create numerous jobs in construction, installation, maintenance, and operations [42–44]. Developing local renewable energy industries stimulates economic growth and provides employment opportunities, particularly in rural areas.

2.5.2 *Environmental and health benefits*

The main benefit of this is the reduction in greenhouse gas emissions, mitigating the impacts of climate change. This is crucial for Southern Africa, which is vulnerable to climate-related events such as droughts and floods. Some expects in energy studies noted that renewable energy technologies produce little to no air pollution, leading to improved air quality [40, 45]. This may reduce the incidence of respiratory and cardiovascular diseases, lowering healthcare costs and enhancing public health.

2.5.3 *Technological and innovation opportunities*

Investing in renewable energy drives technological innovation and development. This includes advancements in energy storage, smart grids, and efficient energy systems, positioning Southern Africa as a leader in the clean energy transition.

To conclude this section, Southern Africa can reduce its dependence on fossil fuels, which are both finite and harmful to the environment. Furthermore, by harnessing its renewable energy potential, Southern Africa can also become a leader in the global transition toward clean energy, attracting investment and creating new economic opportunities in the process. Additionally, the region's abundant natural resources, such as solar and wind power, can be utilized to provide reliable and affordable energy to rural communities that are often left behind in the race toward modernization. By prioritizing renewable energy, Southern Africa can create a brighter future for its residents while also contributing to the global effort to combat climate change.

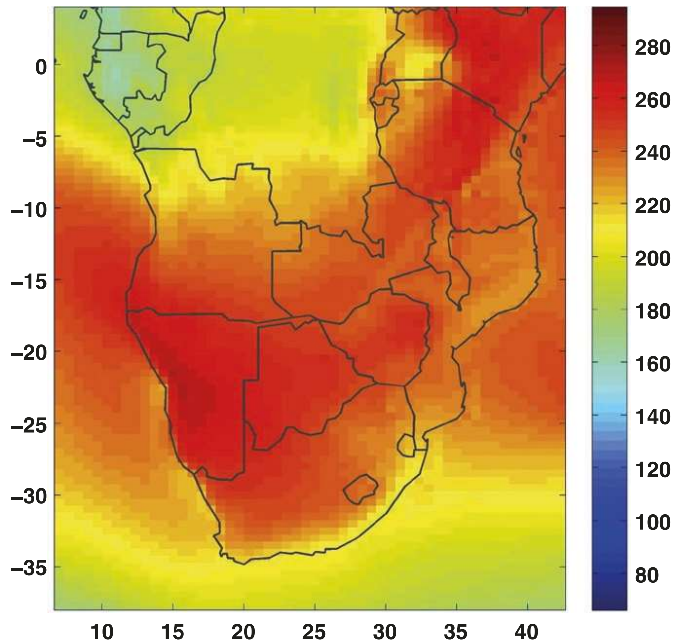


Figure 1. Geographic distribution of average global horizontal irradiance (W/m^2) across Southern Africa [47].

3. Potential RES

Southern Africa stands at a pivotal juncture in its energy evolution, with a diverse array of RES poised to transform the region's energy landscape. As the global shift toward sustainable energy gains momentum, Southern Africa can harness its abundant natural resources to reduce dependency on fossil fuels and promote energy security.

3.1 Solar energy

3.1.1 *Resource availability*

The southern region of Africa is endowed with some of the highest solar irradiance levels in the world, making it an ideal region for harnessing solar energy [46]. Countries like Namibia, Botswana, and South Africa experience abundant sunlight throughout the year, providing a substantial and consistent energy resource. The region's vast, arid landscapes are particularly suitable for large-scale photovoltaic (PV) installations and concentrated solar power (CSP) systems, which can efficiently convert sunlight into electricity. Fant *et al.* [47] mapped the global horizontal irradiance of Southern Africa using the MERRA (Modern-Era Retrospective for Research and Analysis) reanalysis dataset. It is evident from Fig. 1 that the surface global horizontal irradiance is highest in the southwest, surrounding Namibia and extending into Zimbabwe, as well as in the northeastern regions of Tanzania and Kenya.

3.1.2 *Technological options*

3.1.2.1 Solar PV

A study by Ebhota and Tabakov [48] assessed the solar PV potential and performance of a household in Durban, South Africa. The authors reported a global horizontal irradiance of 1659.3 kWh/m^2 and a direct normal irradiation of 1610.6 kWh/m^2, yielding an annual PV energy of 8639 kWh, demonstrating the significant potential of solar PV. In Zimbabwe, the government has been licensing several independent power producers to develop and operate solar power projects, aiming to boost the country's renewable energy capacity and enhance energy security. For instance, Centragrid (Pvt) Ltd is an independent power producer authorized to own, fund, build, and run a 25-MW solar power facility [49]. The company successfully commissioned 2 MW of its licensed capacity, and expansions are underway to increase the capacity of the power plant. The aim is to create enduring value by helping to create a country powered by clean, affordable, renewable electricity.

3.1.2.2 Concentrated solar power

Southern Africa holds significant potential for CSP due to its vast areas of high solar irradiance, particularly in regions such as the Kalahari and Namib deserts [50]. These areas receive consistent and intense sunlight, making them ideal for CSP technologies, which can generate large-scale, reliable, and dispatchable electricity. The ability of CSP to store thermal energy and provide power even when the sun is not shining makes it a valuable addition to the energy mix, offering a stable and sustainable solution to the region's growing energy demands. Tlhalerwa and Mulalu [51] assessed the potential of CSP in Botswana using detailed geographic information system (GIS)-based land exclusion criteria and land-use data to evaluate land suitability in the country. The authors reported that the country has approximately 220 016 km^2 of land available to support CSP. Assuming the deployment of dry-cooled parabolic trough collector CSP plants, the available land area could support an estimated nominal capacity of 3189.54 TWh per year. This potential positions Botswana as a key player in the regional renewable energy landscape, capable of contributing significantly to energy security and sustainability in Southern Africa.

Another study by Duvenhage *et al.* [52] optimized the CSP potential in South Africa using an improved GIS analysis. The findings of the research indicate that over 104 billion square meters of suitable land area are available, offering a theoretical potential to generate more than 11 000 TWh of electricity. It is evident that Southern Africa has strong potential for CSP development, given its vast areas with high solar irradiance. Various CSP technologies, including parabolic trough collectors, solar dishes, central receiver systems, and linear Fresnel reflectors (Fig. 2), can be effectively

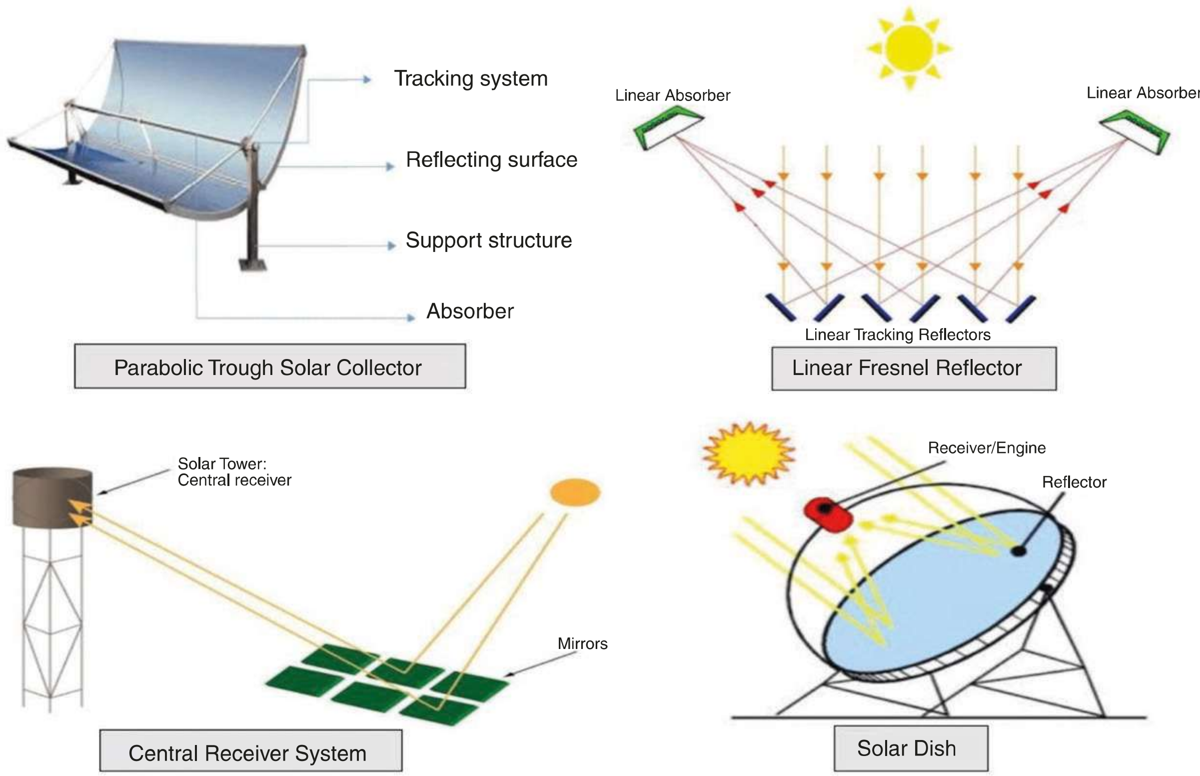


Figure 2. Illustration of various CSP technologies [53].

implemented to harness this abundant solar energy, providing a reliable and sustainable electricity supply for the region.

3.2 Wind energy

3.2.1 *Resource potential*

Southern Africa possesses considerable wind resource potential for power generation, particularly along coastal regions, and highland areas where wind speeds are consistently strong [54]. Countries such as South Africa and Namibia have already identified several high-potential sites suitable for onshore and offshore wind farms, promising significant contributions to the region's renewable energy capacity. Figure 3 shows the average wind speed over Southern Africa. As illustrated, most of the onshore wind resources in the SADC region are concentrated in the southern and northeastern areas, with moderate wind speed clusters scattered in between. A significant expanse of low wind speeds is observed in the northwestern part of the region, covering the Congo River Basin countries and nearly all of Angola.

3.2.2 *Technological options*

3.2.2.1 Onshore wind systems

Onshore wind turbines are wind energy systems installed on land to harness wind power for electricity generation. Fant *et al.* [55] characterized the wind power resource in Southern Africa. The study reveals that while South Africa has a higher mean Wind Power Density compared with its neighboring countries, its wind power resource is less consistent than in other regions of Southern Africa, such as central Tanzania. Additionally, it was found that South Africa's wind potential fluctuates over different timescales, showing greater reliability in the summer compared with winter, and during the day compared with nighttime.

Wind energy is becoming a significant part of South Africa's energy mix, with over 30 utility-scale wind projects now in operation. Notable projects include the Roggeveld wind farm with a capacity of 147 MW [56], the Soetwater wind farm also at 147 MW [57], and the Longyuan Mulilo wind farm at 144 MW [58].

3.2.2.2 Offshore wind turbines

Southern Africa's potential for offshore wind turbines is substantial, particularly along its extensive coastline with high wind speeds and consistent wind patterns. Offshore wind farms can generate significant amounts of electricity due to stronger and more stable winds at sea compared with onshore sites [59]. The coastal regions of South Africa, Mozambique, and Namibia are especially promising for offshore wind development. These areas can leverage advanced turbine technology to maximize energy output and contribute to the diversification of the regional energy mix. Moreover, offshore wind farms can reduce land-use conflicts and have a lesser visual impact, making them a favorable option for sustainable energy generation [60]. Despite the high initial investment and technical challenges associated with offshore installations, the long-term benefits, including increased energy security, job creation, and environmental sustainability, make offshore wind a promising avenue for Southern Africa's renewable energy future.

3.3 Hydro energy

Southern Africa is home to several major hydro schemes that play a crucial role in the region's energy infrastructure. Key projects include the Kariba Dam on the Zambezi River, which provides significant hydroelectric power to both Zambia and Zimbabwe [61], and the Cahora Bassa Dam in Mozambique [62], one of the largest hydroelectric projects in Africa. Additionally, the Inga Dams on

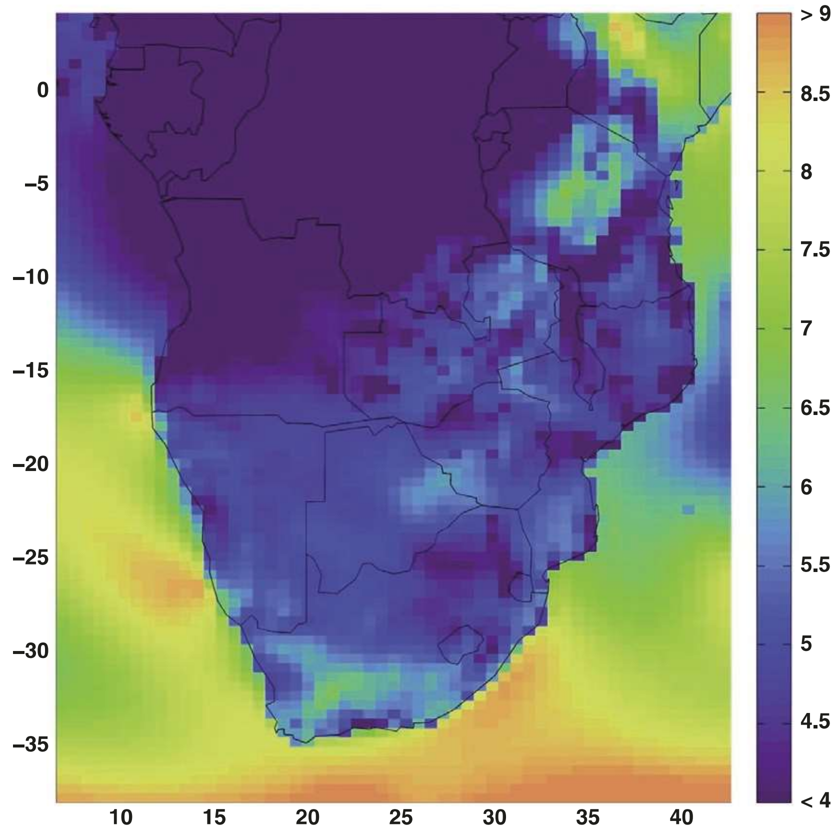


Figure 3. Geographic distribution of average wind speeds (m/s) across Southern Africa [47].

the Congo River in the Democratic Republic of Congo have immense potential for future hydroelectric development [63].

The Kariba Dam, located on the Zambezi River at the border between Zambia and Zimbabwe, has a capacity of approximately 1830 MW and was commissioned in 1959. As one of the largest man-made reservoirs in the world, Kariba Dam is a cornerstone of energy supply for both Zambia and Zimbabwe, playing a crucial role in regional electricity generation [61]. Another key hydropower project is the Cahora Bassa Dam, situated on the Zambezi River in Mozambique. With a capacity of around 2075 MW, it was commissioned in 1974. As one of Africa's largest hydroelectric projects, Cahora Bassa Dam is vital to Mozambique's power generation and exports a substantial amount of electricity to neighboring countries, including South Africa [64]. The dam contributes significantly to the national grid and is a key asset for regional energy security.

In addition to the well-established hydropower schemes in the region, mini-hydropower systems offer significant potential for diversifying Southern Africa's energy mix. In Lesotho, there are five small-scale hydropower plants: Katse (540 kW), Mantsonyane (2 MW), Semonkong (180 kW), Tlokoeng (670 kW), and Tsoelike (400 kW). Currently, only the Katse and Semonkong plants are operational [65]. According to Taele *et al.* [66], Lesotho is well-suited for developing small hydropower systems due to the availability of hydropower resources and a rural settlement pattern that supports decentralized energy systems. In Zimbabwe, three small hydro plants are connected to the national grid: the 750 kW Rusito Scheme in the Chimanimani area and the Pungwe and Nyamhingura systems in the Honde Valley. Additional small hydropower plants include installations at Aberfoyle (35 kW), Claremont (250 kW), Kwenda (75 kW), Mutsikira (3 kW), Nyafaru (20 kW), Sithole-Chikate (30 kW), and Svinurai (10 kW). Ngangani Renewable Energy developed the 1.1 MW Nyamhingura hydropower plant in the Honde Valley and recently commissioned the 2.75 MW Pungwe plant [65]. Across the region, countries are making significant efforts to expand hydropower capacity through mini-hydro schemes to provide power to rural and remote areas.

3.4 Biomass and bioenergy

3.4.1 *Sources of biomass*

Southern Africa holds significant potential for biomass energy production, with abundant sources such as agricultural residues, forestry waste, and municipal solid waste (MSW). These biomass resources offer sustainable and renewable means to diversify the region's energy mix and reduce dependence on fossil fuels.

3.4.1.1 Agricultural residues

Agricultural residues, including crop stalks, husks, and straw, are abundant in Southern Africa due to the region's extensive agricultural activities [67, 68]. Crops like maize, wheat, rice, and sugarcane generate substantial amounts of residues that can be converted into bioenergy. For instance, bagasse, the fibrous byproduct of sugarcane processing, can be used in cogeneration plants to produce both electricity and heat [69]. Utilizing agricultural residues not only provides an RES but also helps in managing agricultural waste, reducing the need for open burning, and mitigating air pollution.

3.4.1.2 Forestry waste

Forestry activities in Southern Africa produce considerable amounts of waste, including tree trimmings, sawdust, and bark

[70]. These byproducts can be harnessed for bioenergy through processes such as combustion, gasification, and pyrolysis. Countries with extensive forestry operations, like South Africa and Mozambique, have significant potential to develop biomass energy projects based on forestry waste. This not only supports the energy sector but also promotes sustainable forestry practices and reduces environmental impacts associated with waste disposal.

3.4.1.3 Municipal solid waste

MSW is another promising source of biomass energy in Southern Africa. Urbanization and population growth are increasing the volume of waste generated in cities across the region. Waste-to-energy (WtE) technologies can convert MSW into electricity and heat through processes like incineration, pyrolysis, and anaerobic digestion [71]. WtE projects address waste management challenges, reduce greenhouse gas emissions, and provide a reliable energy source by diverting waste from landfills and converting it into energy [71, 72]. Countries like South Africa and Namibia are exploring WtE initiatives to harness the energy potential of MSW while improving urban waste management systems.

3.4.2 *Bioenergy technologies*

3.4.2.1 Biogas production

Biogas production involves the anaerobic digestion of organic materials such as agricultural waste, animal manure, and food waste to produce biogas, a mixture of methane and carbon dioxide [73]. Biogas can be used as a clean and renewable fuel for cooking, heating, and electricity generation. In Southern Africa, biogas digesters are increasingly being adopted in rural areas, particularly in agricultural communities. Notable commercial biogas projects include the New Horizons Energy biogas plant in Cape Town, South Africa. The plant was built to process a massive portion of Cape Town's MSW, amounting to around 8000 tons per day, using anaerobic digestion to produce biogas. One of the plant's key outputs was biomethane, with a daily production capacity of about 670 cubic meters. This biomethane production translates to an annual energy output of 600 gigajoules (GJ), equivalent to a 5 MW biogas-to-electricity production capacity. The processed biomethane is not used for electricity generation but instead undergoes cleaning, upgrading, and pressurization to meet standards for use as a natural gas substitute. This final product, known as bio-compressed natural gas (Bio-CNG), is then sold to Afrox, contributing to the region's sustainable energy supply, and reducing dependence on fossil fuels [74].

3.4.2.2 Biofuel processing

Biofuel processing refers to the conversion of biomass into bioethanol, biodiesel, or bio-gasoline using fermentation, distillation, and chemical processes. This RES is derived from biomass such as sugarcane, maize, and jatropha, with Southern Africa being a notable region for biofuel production [75]. In South Africa, key projects include the South African Breweries (SAB) Bio-Energy Plant in KwaZulu-Natal, Illovo Sugar's Ethanol Plant in Mpumalanga, and Biocatalyst in Mpumalanga, which contribute significantly to the country's biofuel industry. Similarly, Darling Biodiesel in Western Cape and Free State Oil in Free State Province are noteworthy projects in biofuel processing. Bioethanol, commonly produced from sugarcane in Southern Africa, is utilized as a blend with petrol for vehicles, showcasing its importance in the transportation sector. Moreover, biodiesel derived from oilseed crops like jatropha, soybean, and sunflower is gaining popularity as a sustainable fuel option for various applications [76]. In Zimbabwe, bioethanol production from sugarcane and biodiesel production from *Jatropha curcas* demonstrate the region's commitment to expanding its biofuel sector and reducing reliance on traditional fossil fuels.

3.4.2.3 Biomass power plants

Biomass power plants in Southern Africa play a crucial role in utilizing organic materials like wood chips, agricultural residues, and energy crops to generate electricity and heat. These plants employ a range of technologies such as combustion, gasification, and pyrolysis to convert biomass into energy [77]. Notable examples in the region include the Ngodwana Biomass Power Plant in Mpumalanga, South Africa, which utilizes biomass residues from the forestry industry to generate renewable electricity [78]. In Zimbabwe, the Triangle Biomass Power Plant utilizes sugarcane bagasse, a byproduct of sugar production, to produce electricity for the national grid [74]. These biomass power plants are particularly significant in rural areas with limited access to grid electricity, providing reliable and sustainable power while contributing to local economic development through biomass supply chains and job creation in the bioenergy sector.

3.4.2.4 Emerging technologies

Key innovations such as green hydrogen production, hybrid energy systems, and advanced energy storage solutions are promising solutions to enhance energy security, sustainability, and economic growth in the region.

Green hydrogen, produced by using RES like solar and wind to power electrolysis, is gaining traction as a clean fuel with significant potential for both domestic use and export markets [79]. Southern Africa, with its abundant renewable resources, is well-positioned to become a global leader in green hydrogen production. Countries such as Namibia and South Africa are investing in green hydrogen projects to leverage their vast solar and wind resources. The development of green hydrogen infrastructure not only supports the decarbonization of the energy sector but also offers new economic opportunities through the export of green hydrogen to international markets, particularly to regions with high energy demand and stringent emissions targets, like Europe and Asia.

Hybrid energy systems, which combine multiple renewable sources such as solar and wind, offer a reliable and efficient solution to the region's energy needs. Hybrid systems can provide a more stable power supply, mitigating the intermittent issues associated with single-source renewable energy systems [80]. In Southern Africa, several projects are exploring the potential of solar–wind hybrid systems to enhance grid stability and reduce reliance on fossil fuels. For example, hybrid projects in South Africa and Botswana are demonstrating the effectiveness of these systems in providing continuous and reliable electricity, especially in remote and off-grid areas [81]. The synergy of solar and wind resources in hybrid systems can optimize energy generation throughout the day and across different seasons, making it a viable option for sustainable energy development.

Advanced energy storage solutions are crucial for maximizing the benefits of renewable energy by addressing the challenges of intermittent and ensuring a stable power supply. In Southern Africa, a variety of storage technologies are being explored and implemented, including batteries, pumped hydro storage, and thermal storage [82]. Battery storage systems, such as those being deployed in South Africa, are essential for grid stabilization and providing backup power during periods of low renewable generation [83]. Pumped hydro storage, which uses excess renewable energy to pump water to higher elevations for later use in electricity generation, offers large-scale energy storage capacity [84]. Additionally, thermal storage systems, which store heat energy for later conversion to electricity, are being developed to complement solar thermal power plants [85]. These energy storage solutions not only enhance the reliability and efficiency of renewable energy systems but also support the integration of higher shares of renewable energy into the grid.

4. Impacts of RES

Southern Africa stands at a pivotal juncture in its energy evolution, with a diverse array of RES poised to transform the region's energy landscape. As the global shift toward sustainable energy gains momentum, Southern Africa can harness its abundant natural resources to reduce dependency on fossil fuels and promote energy security. This transition to renewable energy brings significant economic, social, political, and environmental impacts.

4.1 Economic impacts

The development and deployment of RES such as solar, wind, and biomass are creating new economic opportunities in Southern Africa. Investments in renewable energy projects generate employment across various sectors, from manufacturing and installation to maintenance and operations [86]. For instance, large-scale solar projects in Namibia and Botswana, as well as wind farms in South Africa, have spurred job creation and fostered local industries. Additionally, renewable energy can reduce energy costs in the long term, contributing to economic stability and growth [87]. The burgeoning bioenergy sector, with projects like the SAB Bio-Energy Plant in KwaZulu-Natal and Illovo Sugar's Ethanol Plant in Mpumalanga, showcases the potential for biofuel production to support local economies by creating new markets for agricultural residues and other biomass sources [78, 88].

4.2 Social impacts

Renewable energy projects significantly improve energy access, particularly in rural and remote areas where traditional grid electricity is limited or unavailable [89]. Mini-hydropower systems in Lesotho and biomass power plants in Zimbabwe exemplify how decentralized energy solutions can provide reliable electricity, enhancing the quality of life for local communities. Improved energy access facilitates better education, healthcare, and economic activities, contributing to social development and poverty reduction. Furthermore, renewable energy initiatives promote community engagement and can lead to more equitable energy distribution, ensuring that even the most marginalized groups benefit from clean energy [90].

4.3 Political impacts

The shift toward renewable energy strengthens national and regional energy security by diversifying the energy mix and reducing reliance on imported fossil fuels. This can lead to greater political stability as countries become less vulnerable to global energy market fluctuations and geopolitical tensions associated with fossil fuel supplies [91]. Additionally, the adoption of renewable energy aligns with international climate commitments, enhancing Southern Africa's standing in global environmental agreements and promoting regional cooperation on sustainable energy initiatives. Countries in the region, such as South Africa and Mozambique, are increasingly seen as leaders in the renewable energy transition, bolstering their political influence and fostering stronger international partnerships [92, 93].

4.4 Environmental impacts

Renewable energy projects significantly mitigate environmental degradation and reduce greenhouse gas emissions, contributing to the global fight against climate change [94]. The utilization of solar and wind energy, e.g., produces no direct emissions, and the use of bioenergy from agricultural and forestry waste helps manage waste streams and reduce landfill usage [95]. Notable projects like the Triangle Biomass Power Plant in Zimbabwe illustrate how renewable energy can lead to substantial reductions in carbon footprints. Moreover, the conservation of natural landscapes and biodiversity is supported by the reduced need for fossil fuel extraction and combustion, leading to healthier ecosystems and more sustainable land-use practices [96].

4.5 Detailed analysis of the socio-economic and environmental impacts of renewable energy projects in Southern Africa

A comprehensive analysis of the socio-economic and environmental impacts of renewable energy projects covers multiple dimensions e.g. job creation, economic growth, health benefits, and environmental conservation as shown in Table 1.

Renewable energy projects across the globe offer extensive socio-economic and environmental benefits, entailing job creation, economic growth, health improvements, and environmental conservation. However, to maximize these benefits, robust policy frameworks, effective regulatory environments, and investment in infrastructure are necessary as discussed and reviewed in the next sections.

4.6 The energy policies and regulatory frameworks in Southern African countries

A review of the existing energy policies and regulatory frameworks in Southern African countries reflects on the multifaceted approaches each nation adopts to address energy security, access, and sustainable development as shown in Table 2. The analysis will focus on key countries in the region, including South Africa, Zambia, Zimbabwe, Namibia, Mozambique, and Botswana, analyzing their policies, renewable energy targets, investment confidence, and regulatory challenges.

Countries in Southern Africa use different ranges of energy policies and regulatory frame works to push renewable energy initiatives. Currently, South Africa has the highest installed renewable energy capacity in the region, other countries like Zambia and Namibia are making progress but encounter substantial infrastructural and financial hurdles. On the other side Zimbabwe and Mozambique, with ambitious renewable energy targets, struggle with economic and political instability, which affects policy implementation and investor confidence.

While comparing and matching Southern African countries' energy policies and regulatory frameworks with international best practices like the European Union National Energy and Climate Plans, several areas for improvement and alignment arise. International best practices are generally characterized by robust policy frameworks, effective regulatory environments, clear targets, and incentives for renewable energy adoption, as well as strong governance and regional cooperation. To address these, the following policy recommendations will assist Southern African countries to elevate their energy policies and regulatory frameworks:

- Implementation of Integrated Regional Energy Planning
- Improve Governance and Policy Implementation
- Promotion of Regional Cooperation and Cross-Border Energy Trade

Table 1. Detailed analysis of the socio-economic and environmental impacts of renewable energy projects.

Impact category	Detailed analysis
Socio-economic • Economic growth • Job creation • Health benefits	Renewable energy (RE) projects contribute to economic growth by attracting investment companies, reducing energy costs, and stimulating local industries [97]. Adoption of renewable energy technologies has increased the gross domestic product (GDP) of many countries e.g. South Africa has attracted over ZAR 300 billion renewable energy investments [21]. As of 2023, the renewable energy industry has employed approximately 13 million people across the globe [98]. Reduction in air pollution, by replacing fossil fuels with RES [99]. Health cost savings, a study in the USA highlights that replacing fossil fuels with renewable energy could save money thus reducing coal with RES can save USD 4.7–34.3 billion in health costs annually in some regions.
Environmental • Reduction in emissions • Ecosystem protection • Water conversation	Renewable energy projects reduce emissions of greenhouse gases [100]. Reduction in air pollution, thus reduction of harmful pollutants like sulfur dioxide and nitrogen oxides [101]. It was estimated in 2018 that the use of renewable energy technologies avoided approximately 3 giga-tons of carbon dioxide therefore underscoring the significant environmental benefits of transitioning to renewable energy [102]. The use of RES helps in protecting the ecosystems by reducing reliance on fossil fuels like coal, which causes extreme environmental degradation through activities such as mining, drilling, and deforestation [42, 103].
Techno-economic • Increased energy production and energy independence • Increased investments in renewable energy hence, increased employment opportunities, technological advancement, etc. • Reduced energy demand • Reduced energy costs	Southern African countries have a huge potential for generating renewable energy. This can be leveraged to address their energy demands. For example, South Africa's peak energy demand is at 20 000 GWh and wind energy alone contributes approximately 900 GWh [104]. This shows the large potential energy mix has on compensating for the energy demands, especially during peak periods. The net present value (NPV) gives the present-day worth of the future net cash flow of a project and a positive value denotes a gain for the investor. As an example, a project in [105] had an NPV of R6.58 million. A positive NPV attracts investors since it offers them great economic benefits [105]. Regarding solar PV systems, the implementation of tracking systems increases productivity. Systems that can be adopted include vertical-axis tracking and continuous two-axis tracking systems among others. The systems are technically feasible and enhance energy generation [46]. The time-of-use (TOU) strategy can be adopted to match maximum RE generation with peak energy demand periods. This relieves electric grids by reducing peak load demands. RE sources significantly contribute to energy savings, especially for commercial systems with short payback periods. This is also fueled by the decline in installation costs recently noticed [82].

Therefore, by addressing the existing gaps in policy frameworks, regulatory environments, and governance structures, Southern African countries can create a more robust environment for renewable energy investments and regional cooperation for sustainable development.

4.7 Renewable energy profiles in Southern Africa

The energy profiles of Southern African countries reflect a diverse mix of RES and varying levels of installed capacity as shown in Table 3. The diverse renewable energy profile across Southern Africa reflects each country's unique energy sources, different economic conditions, and policy environments. Nevertheless, some countries have made significant moves in adopting renewable energy, others face different barriers that must be addressed to accelerate the region's transition to sustainable energy.

South Africa leads the region with the largest installed renewable energy capacity. The country has a well-developed renewable energy sector supported by government policies. However, South Africa still relies on coal. Zambia and Mozambique have both increased their renewable energy capacities with a moderate growth rate. Renewable energy adoption in Namibia is increasing steadily however small markets and reliance on other sources limit further growth. In Zimbabwe, the adoption of renewable energy is hindered by economic problems and regulatory policy challenges. However, there is potential in hydro and solar energy, but the country has struggled to attract the necessary investment. Botswana's adoption rate is very low, reflecting a cautious approach to renewable energy use and over reliance on imports. Future efforts regarding adoption should focus on enhancing regional cooperation, addressing infrastructural challenges, political issues, and financial barriers therefore developing tailored policies that increase the rate of adoption enhancing sustainable development.

4.8 Installed renewable energy capacity and trends in Southern Africa

According to the IRENA, Africa's energy mix in 2022 was dominated by traditional and nonrenewable sources [106]. Figure 4 illustrates the continent's total energy supply by source, measured in terajoules (TJ). The data highlights biofuels and waste as the most significant energy source, contributing 13 097 035 TJ, followed by oil (8 816 164 TJ) and natural gas (5 953 057 TJ). Coal remains a major contributor at 4 395 726 TJ. Renewable sources, including hydro (581 165 TJ) and wind, solar, and other renewables (377 672 TJ), accounted for a relatively smaller share. Nuclear energy contributed 106 941 TJ, underscoring its limited role in Africa's energy landscape. These statistics reveal both opportunities and challenges for Africa's transition to renewable energy in the southern region.

Figure 5 highlights the regional trend in renewable energy adoption from 2012 to 2022, showing steady growth over the decade. The capacity increased from 120 611 GWh in 2012 to 204 502 GWh in 2022, reflecting an overall growth rate of approximately 70%. This upward trajectory signifies a gradual but consistent effort to integrate RES across the continent. Notably, significant growth occurred from 2017 to 2022, during which capacity increased by nearly 55 874 GWh. However, the pace of adoption remains slower than required to achieve Africa's energy transition goals. Despite

Table 2. Existing energy policies and regulatory frameworks in Southern African countries.

Country	Policy framework	Aim	Regulatory environment
South Africa	1. Integrated Resource Plan (IRP) 2. REIPPPP Program	1. IRP outlines the energy mix, emphasizes on renewable energy adoption 2. REIPPPP drives renewable energy projects in the country	1. National Energy Regulator of South Africa (NERSA): the NERSA regulates the electricity sector, including tariffs and licensing
Zambia	1. National Energy Policy (NEP) 2. Renewable Energy Feed-in Tariff (REFIT)	1. NEP promotes energy efficiency, diversify energy sources, and increase access to electricity 2. The REFIT supports small-scale renewable energy projects	1. Energy Regulation Board (ERB): the board oversees the regulation of electricity
Zimbabwe	1. National Renewable Energy Policy (NREP) 2. Rural Electrification Policy (REP)	1. NREP aims to boost the share of renewable energy in Zimbabwe's energy mix 2. REP devotes itself to expanding energy access in rural areas	1. Zimbabwe Energy Regulatory Authority (ZERA): ZERA regulates the energy sector, thus electricity generation, transmission, and distribution across the country
Namibia	1. National Energy Policy (NEP)	1. NEP targets ensuring energy security and promoting renewable energy	1. Electricity Control Board (ECB): the board regulates power licenses and promotes renewable energy
Mozambique	1. The National Energy Strategy 2. Renewable Energy Plan	1. National Energy Strategy aims to increase electricity generation in the country	1. National Directorate of Energy (NDE): the NDE oversees the regulation and development of the energy sector

Table 3. The energy profiles of Southern African countries.

Country	Estimated installed renewable capacity (MW)	Main RES	Challenges in adoption
South Africa	10 000	Solar, wind, hydro	Policy frameworks, infrastructure
Zambia	3500	Solar, hydro	Financing capital, lack of infrastructure
Zimbabwe	750	Hydro, solar	Poor regulatory, political factors, no infrastructure
Namibia	500	Hydro	Small market. Reliance on other sources
Mozambique	2700	Solar, hydro	Political instability, politics, and poor regulatory policies
Botswana	Less 150	Solar	Small market, reliance on imports

the progress, the figures indicate that much of Africa's renewable energy potential remains untapped, with barriers such as limited infrastructure, insufficient investments, and policy inconsistencies continuing to hinder large-scale adoption. Critically, while the growth trend is promising, it pales in comparison to global averages and the continent's potential for solar, wind, and hydroelectric power generation. Moreover, the data underscore the need for enhanced regional cooperation, financial mechanisms, and technology transfer to accelerate the deployment of renewables and bridge the energy access gap.

Table 4 highlights the contribution of various RES by country in Southern Africa, expressed as a percentage share and total generation in gigawatt-hours (GWh). Solar PV has the highest percentage contribution in Botswana (100%) and significant representation in Namibia (29.6%) and South Africa (55%). Hydropower dominates the renewable energy mix in most countries, with Zambia (98.6%), Mozambique (99.2%), and Zimbabwe (96.9%) being prominent examples. Biofuels are notably utilized in Eswatini (38.7%) and South Africa (2.9%). Wind energy remains underutilized, with South Africa and Namibia showing minor contributions. Solar thermal energy is present only in South Africa, where it contributes 13.0% (1589.45 GWh) of the renewable energy mix.

The data underscore the reliance on hydropower across Southern Africa, which presents both strengths and vulnerabilities. While it is a mature and reliable RES, dependence on hydropower increases exposure to climate-related risks such as droughts, which are frequent in the region. Solar PV, despite the region's abundant sunlight, is underexploited, with Botswana being the only country where it accounts for 100% of renewable energy generation. Countries like Namibia and South Africa show promise in diversifying their energy mix with solar PV, solar thermal, and wind energy.

5. Case studies in the Southern African region

The average annual 24-h global solar irradiation for South Africa is around 220 W/m^2 and up to 2045 kWh/m^2 can be reached during a year [107]. These values are higher compared with those of Europe and the USA, and notably from the literature, most renewable energy projects in the Southern region are being implemented in South Africa. In a quest to transition from fossil fuels to sustainable renewable energy, South Africa launched a Renewable Energy Independent Power Producer Procurement

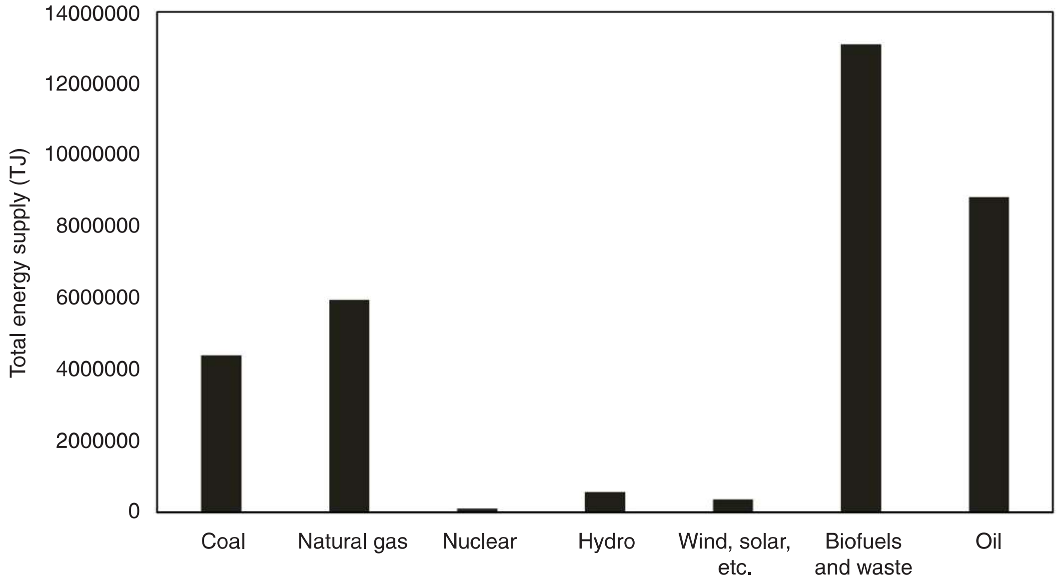


Figure 4. Total energy supply by source in Africa, 2022 (data sourced from [106]).

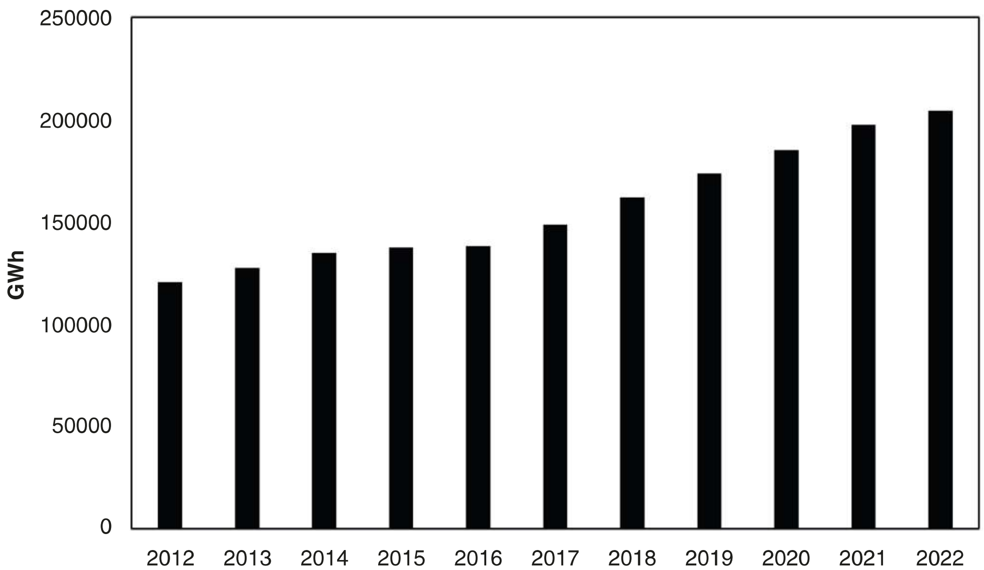


Figure 5. Africa's installed renewable energy capacity (GWh), 2012–2022 (data sourced from [106]).

Table 4. Contribution of RES by country in Southern Africa (% share and generation in GWh) (data sourced from [106]).

Country	Solar PV		Hydropower		Biofuels		Wind		Solar thermal	
	%	GWh	%	GWh	%	GWh	%	GWh	%	GWh
Botswana	100	6.16	-	-	-	-	-	-	-	-
Lesotho	0.3	1.28	99.7	480.26	-	-	-	-	-	-
Malawi	0.7	11.73	96.4	1694.32	2.9	50.76	-	-	-	-
Mozambique	0.4	11.73	99.2	16 183.62	0.4	65.43	-	-	-	-
Namibia	29.6	451.5	69	1052	-	-	1.4	21.6	-	-
South Africa	55	6739.43	26.9	3302.88	2.9	359.87	1.8	223.75	13	1589.45
Eswatini	0	0.08	61.3	296.93	38.7	187.16	-	-	-	-
Zambia	0.9	158.92	98.6	17 130	0.5	78.77	-	-	-	-
Zimbabwe	1.2	76.01	96.9	5974.14	1.8	112.88	-	-	-	-

(REIPPP) program in 2011 [107]. In 2022, South Africa's energy consumption reached 211.5 TW, accounting for 1826.8 g of CO_2eq/kWh greenhouse gas emissions [108]. This poses a serious environmental concern that needs immediate attention hence, more research is being undertaken to resolve this. Fellow Southern African countries, given their harsh economic conditions, are slowly adopting RES, particularly solar PV and WtE technologies.

5.1 Hybrid energy sources (fossil fuels plus RES)

In a quest to mitigate the environmental challenges posed by fossil fuel usage, researchers are also considering the implementation of hybrid energy systems, that is integrating conventional and renewable energy systems, which might also enable the full transition to renewable energy systems. The feasibility of integrating nuclear energy sources and RES together with hydrogen production, for excess energy storage, to supply off-grid locations is evaluated in a case study of a remote South African community by Esteves and Gabbar [108]. The community is in the Northern Cape region with 7000 residents consuming about 163 GWh per year. According to the results, an optimal hybrid system consists of 65% nuclear, 32% solar, and 3% wind energies, therefore, generating 84% nuclear energy, 14% solar energy, and 2% wind energy with a total of $0.092/kWh energy cost [108]. Overall, this hybrid system produces approximately 181 GWh of electricity, avoiding the emission of about 332 000 tons of CO_2, hence, a significant contribution toward resolving climate change issues [108].

5.2 Wind

Notably, wind energy integration has been on the rise in South Africa since 2011 with an installed capacity of 633.99 MW, 3357 MW generated from 36 wind farms in operation as of 2021 [104], and 3.4 GW as of 2022 [108]. Thus, around 9% of its overall installed capacity is contributed by renewables and is expected to increase as the country targets 17.8 GW capacity of renewable energies by 2030 [108]. Of these 36 wind farms, 10 are in the Western Cape, 10 in the Northern Cape, and 16 in the Eastern Cape regions. The wind farms in the Northern Cape, e.g., Garob Wind Farm with a capacity of 144.9 MW, showed greater performance compared with those in the other two regions [104]. According to Eskom, the largest electricity supplier in the country, the peak energy demand is at 20 000 GWh during winter, and wind energy is shown to significantly contribute to the energy demand with around 900 GWh as generation also peaks during that time. To determine the performance of the farms based on their maximum capability, capacity factors are used. The wind farms in South Africa have a 33.43% average capacity factor, exceeding the 25% global average [104]. A wind farm in Great Kei municipality, Eastern Cape, incorporates seven wind turbines rated 3 MW each, thus a total capacity of 21 MW [109]. Ten sites in eThekwini municipality were found to potentially generate 215 MW of wind energy [110]. This shows the greater potential wind energy has toward meeting energy demands.

5.3 Solar PV

Considering solar PV case studies in a South African-based industry, the first one is a micro-grid in Midrand with a PV system of capacity 998 and 140 kW battery storage installed in 2017. The micro-grid incorporates grid-tied PV systems, Siestorage batteries, an SICAM controller, and 30 × SE27.6K inverters. The installation costs for the whole system, inclusive of the cables and micro-grid control that contains an internet of things solution amounting to US$1 615 339.29. By comparing the energy consumption and energy savings before and after the installation of the system, results show that after installation, the consumption decreased by 49.22% in summer and 48.25% in winter, thus about 50% annual cost of consumption. According to the authors, the break-even will be at the ninth year of investment, with additional savings of about US$56 784.47. If battery storage capacity is increased by 50%, the break-even is set to increase by a year. Most importantly, given the yearly increase in electricity tariff rate, the savings are seen to increase per year with the degradation of the solar panels considered [107].

Higher institutions in South Africa are also making efforts to tap into renewable energy technologies to combat load-shedding and conserve energy. As an example, the Center for Energy and Electric Power (CEEP) at Tshwane University of Technology (TUT) installed a 1.3 kW PV system for lighting their solar water heater testing center in Soshanguve [111].

In a study of renewable energy resources in eThekwini municipality in Durban, South Africa, done by [110], Durban is shown to have an average solar radiation of 4.45 kWh/m^2/day, thus 1625 kWh/m^2/yr on average. Pre-feasibility study done on 10 municipal buildings' rooftops showed the potential of generating 2510 kWp of electricity excluding a 580-kW PV system already installed at the MAN truck and bus manufacturing facility at Westmead, Durban. Also, a 53-MW solar PV system can potentially be built at nine old landfill sites with a total of 109 ha [110].

5.4 Waste-to-energy

South Africa, as compared with other Southern African countries, has better MSW management and processing infrastructure, hence the many WtE projects (see Table 5). From a study by Sewchurran and Davidson [110], an estimate of 4000 kW can be generated from wastewater treatment and 19 MW from municipal landfill gas in eThekwini municipality, Durban, and the Tongaat Hullets mills produce 50% of its electricity requirements while exporting around 1 MW to eThekwini grid and 7.3% to the national grid [110]. Annual sugarcane production can potentially produce 960 MW annually from sugar bagasse [21]. South Africa has the potential of generating hydro electricity from wastewater treatment plants. A study in [113] shows between 7.9 and 9.8 kW can be generated using an Archimedes screw turbine at the outflow of the Zandvliet wastewater treatment works in Cape Town. Already, South Africa is generating, e.g., 15 kW from the Pierre Van Ryneveld reservoir in Pretoria and 1.475 MW from the Faure water treatment plant in Cape Town.

As of 2020, six landfill gas to energy (LFGE) projects were in operation generating 15 MW in the Gauteng, KwaZulu-Natal, and Western Cape provinces. These include a privately owned one generating 1.6 MW, and the Jack and Simmer project generating 594 600 kWh, that has reduced around 664 488 CO_2 emissions. Both projects are in Ekurhuleni Municipality. Also, in eThekwini Municipality, there are Mariannhill, Bisasar, and La Mercy projects with ZAR12 million annual operational costs and costed ZAR 114 million to implement. The Mariannhill project produces 900 kWh while the Bisasar one produces 9 MWh per day [114]. Zimbabwe installed a 2.5-MW biogas plant, the Firle Biogas Project, at a sewage treatment plant. Also, with the help of private investors, Harare City Council implemented the Mbare Biogas project that runs a 100- to 200-kVA generator supplying electricity in Mbare. On the other hand, the Harare Institute of Technology, Mutare City Council, and Climatic Change Research Centre proposed the thermal distillation of sewage sludge into diesel and natural gas,

Table 5. Examples of WtE projects in South Africa.

Location	Type of project	Capacity
Mossel bay	Anaerobic digestion of wastewater	4.2 MW
Johannesburg	Anaerobic digestion of sludge	1.2 MW
Bronkhorst-Spruit, Pretoria	Anaerobic digestion (biogas) of Animal manure	4.6 MW
Darling Uilenkraal	Anaerobic digestion (biogas) of Bovine manure	600 kW
Bredasdorp	Anaerobic digestion (biogas) of abattoir waste	100 kW
Grabouw	Anaerobic digestion (biogas) of fruit waste	500 kW

Source: Adapted from [112].

while Bulawayo City Council proposed to generate 110 000 l of biodiesel and 2.2 MW of electricity [114].

5.5 Tidal

Another alternative renewable energy resource, with the least research in Southern Africa, is tidal energy. A tidal resource assessment was carried out for the South African coastline to determine the optimum characteristics for a tidal plant [115]. Since tidal ranges of at least 5 m and tidal currents of at least 1 m/s are suitable for tidal barrage plants and tidal stream plants, respectively, the highest tidal range recorded was 4.50 m at Richards Bay, deeming South Africa unsuitable for implementing barrage plants. Nevertheless, a tidal current, the Agulhas current, with an average velocity of 1.3 m/s and a surface velocity of 2 m/s was recorded on the east coast, and East London was considered a potential site for a tidal farm [115]. Based on results obtained from the proposed plant design, 26.15 kW can be produced by a single turbine, and assuming 60 turbines coupled to an electrical generator of 0.8 efficiencies are used, about 1.3 MW can be generated, which is about half the capacity of the Sol Plaatje hydropower station in Free State, South Africa [115].

5.6 Others

With a generation capacity of 2.9 GW, Zambia generated 14.40 TWh annually, as of 2018, and has an estimated increase of 28.14 TWh energy deficit by 2035. Authors in [116] conducted a techno-economic analysis for the Zambian case suggesting a mixture of renewable energy technologies as a way out. An estimation of 386.98 MW large hydropower, 5.09 MW small hydropower, 2.91 MW geothermal, 152.76 MW solar PV, 10.18 MW biomass, and 27.16 MW wind, totaling 585.08 MW average annual generation capacity, was deemed an optimal solution [116]. A renewable energy mix capacity of 10.5 GW targeted between 2019 and 2035 would require an investment of US$899.94 million per year for 18 years, accounting for 65.9% large hydropower, 0.86% small hydropower, 2.41% biomass, 4.81% wind, 24.75% solar PV, and 1.3% geothermal, with levelized cost of energy between 39 and 89 M$/Wh. For a 7-year payback period and net present value set at 50% initial investment cost, the renewable energy feed-in tariff of hydropower and biomass would be at most 70 M$/Wh [116].

Motjoadi *et al.* [105] used HOMER software to model and optimize a grid-connected hybrid microgrid from various energy sources to derive an optimal techno-economic solution for the Lebowakgomo community in Limpopo province, South Africa. A total of 300 households, each with six people on average, were studied. According to data gathered from the National Renewable Energy Laboratory (NREL), an annual average solar irradiance of 5.66 kWh/m^2/day with 6.964 kWh/m^2/day being the maximum irradiance, and an average annual temperature of 19.52°C was used. 700 kWh/day was deemed an annual average load with 85.53 kW as a peak load [105]. From the results, a hybrid system composed of 1.252 kW solar PV, 224 kWh battery storage capacity, 30 kW wind, and 459 kW power converter tied to the grid is selected as the best solution for this case as it presents a net present cost (NPC) of R6.58 million, R0.151 cost of energy, and operational costs of R2919 which are the lowest values compared with other options. A maximum renewable energy fraction of 85.9% also means the system has less carbon emissions, hence it is environmentally friendly. All in all, this grid-tied microgrid system produces 2 507 054 kWh/yr of electricity and has a load consumption of 1 742 834 kWh/yr [105].

Lesotho's energy demand is at 196.41 MW whilst generating 74.7 MW at the Muela Hydropower Plant (MHP). A 20-MW solar power plant is being constructed and plans are for it to be grid-tied. Considering a 60-MW solar PV plant in Ha-Ramarothole and a 36-MW wind farm in Lets'eng to be tied to Lesotho's electricity grid, Kao et al. [117] explored different integration possibilities that can meet the country's energy demand. Given a scenario of generating power from MHP and importing some, adding solar energy reduces the imports from 41% to 30% and a total of 6.07 GWh can be exported. Adding the 36 MW wind energy to that further reduces the imports to 22% and an average of 2.9 GWh would be exported per month [117].

6. Challenges faced in implementing renewable energy projects

6.1 Considering off-grid systems

Despite efforts to have an adequate energy supply, the ever-changing energy demand is a huge obstacle to the transition from fossil fuels to renewables, hence the continued efforts for solutions for a stable energy supply. Development of commercial solar PV farms requires lots of land which is expensive and not always readily available. To make informed decisions about a power generation system that involves various energy sources, and energy modeling tools can be used. They consider factors like energy demand, available resources, etc., and do a comprehensive economic evaluation, outputting the NPC, cost of energy among other factors [108]. The sites at which wind farms can be placed must be considered in determining the viability of wind energy generation. This is evident in [104] where wind farms in the Western Cape and Eastern Cape regions underperformed compared with those in the Northern Cape, due to variable wind speed profiles in their respective regions [104]. Poor site selection results in insufficient generation capacity, hence a lesser contribution to the energy supply than the system's maximum potential [108].

Another big challenge in the implementation of RES, particularly in the context of Southern African countries, is that the technology is new, hence the lack of local expertise [116]. Also, in a study of solar water heaters projects in QwaQwa, South Africa, social acceptance proved to have a considerable impact on the success of renewable energy projects [113]. As indicated by Mbazima *et al.* [114], the transition to renewable energy generation in Southern Africa is hindered by limited economic investment, poor maintenance, limited waste processing facilities, and abundant and easily accessible coal reserves. As an example, the La Mercy LFGE project in Ekurhuleni, South Africa, was decommissioned due to a lack of proper maintenance [117]. On the other hand, the intermittent nature of renewable energy technologies must be considered during site selection for constructing off-grid renewable energy generation systems, thus evaluating wind speed profiles for wind farms, solar irradiation for solar PV systems, and proximity of waste disposal sites for WtE technologies. Determining the peak hours can assist energy producers in preparing alternatives at times when the demand is high [104].

6.2 Considering grid-tied systems

The biggest issue with a transition from fossil fuel-based energy generation to renewable energy one lies within grid integration. The penetration of RES into power grids is estimated to increase to 85% in 2050 [118], thus accelerating the net-zero carbon emissions goal of decarbonizing the power grids. When considering grid-tied systems, the site on which the system is to be installed must be closer to the grid to reduce installation costs [110]. For better performance, RES can be grid-tied and electronic converters are used in the connection. This introduces a bigger challenge to the grid. Since RES are naturally intermittent, a large-scale integration into the grid results in a transition of the power system from being a synchronous generator (SG)-based to an inverter-based one with low inertia [119]. It's predicted that at some point in the future, the weight of RES will exceed that of SGs in the grid and, the frequency response will drastically decrease at 60%–80% RES penetration [120].

An RES-dominated power system's main challenge is the significant reduction in rotational inertia which disturbs its overall dynamic behavior since the conventional systems relied on SGs for the provision of inertia and grid stability [121]. According to [119], inertia is a physical characteristic of rotating machines to immediately respond to a change in active power output caused by a frequency change in a network [119]. Inertia poses a risk of preventing full-scale integration of RES, hence the need to ensure frequency stability [121]. Below the critical inertia point, the response mechanisms will not be able to regulate system stability [120].

Consequently, the increased penetration of RES into the grid results in catastrophic events like system blackouts and load shedding [119]. Naturally, inverters/converters do not provide system inertia e.g. ac-dc-ac converters in some wind turbines even decouple the wind inertia in the grid leading to a rapid increase in the rate of change of frequency and frequency deviations [120]. According to [121], high penetration of RES causes power imbalance and voltage drop in transmission lines, frequency mismatch with the power grid, and imbalance in production or consumption in distribution loads [121]. In terms of frequency stability regulation, energy storage systems suffer from reserved power losses, charge/discharge cycles, etc., and on the other hand, the power-inverting electronics suffers from power conversion and frequency measurement delays making it difficult to stabilize the frequency [121]. Now given these problems and considering the economic statuses of Southern African countries, a full transition to an RES-dominated power system (grid-tied) is very challenging. However, an energy mix or developing off-grid renewable energy projects is viable. Considering remote areas, a full transition from fossil fuel-based to renewable energy-based power generation systems can be challenging since there is no or insufficient transmission infrastructure as stated by [108], hence shunning the idea of having grid-tied systems.

7. Recommendations on transitioning from fossil fuels to renewable energy for the Southern African region

Transitioning from fossil fuels to renewable energy in the Southern African region presents both significant opportunities and substantial challenges. From the study, political factors and limited economic investment are common challenges when considering this transition. Hence, regional cooperation is required to promote and accelerate the implementation of RES projects and to develop a unique set of operational and safety standards most suitable for the region. Also, considering grid-tied RES, grid infrastructure such as grid capacity must be improved. To ensure a smooth and effective transition, the following recommendations can be adopted, and future work will focus on developing a comprehensive roadmap for this transition targeted at the Southern African region.

7.1 Develop comprehensive policy frameworks

Governments should set clear, measurable, and ambitious renewable energy targets. These targets should align with national development plans and international commitments such as the Paris Agreement. Regular reviews and updates of these targets will ensure they remain relevant and achievable. Southern African nations can also introduce policies that encourage investment in renewable energy technologies. These can include tax incentives, subsidies, feed-in tariffs, and grants for research and development. Regulatory frameworks should be streamlined to reduce bureaucratic hurdles for renewable energy projects.

7.2 Enhance infrastructure and grid capacity

Invest in modernizing the existing grid infrastructure to handle the integration of RES. This includes expanding grid capacity, implementing smart grid technologies, and enhancing transmission and distribution networks to minimize losses and improve reliability. Additionally, encourage the development of decentralized energy systems such as mini-grids and off-grid solutions. These systems can provide reliable electricity to remote and underserved areas, reducing dependency on centralized fossil fuel-based power plants.

7.3 Foster regional cooperation and integration

Promote the development of regional energy markets through the Southern African Power Pool and other regional initiatives. This will enable better resource sharing, improve energy security, and optimize the use of renewable energy resources across borders. Also to work toward harmonizing technical standards and regulatory frameworks across the region. This will facilitate cross-border investments, reduce transaction costs, and ensure that renewable energy projects meet consistent quality and safety standards.

7.4 Address social and environmental impacts

Ensure that renewable energy projects consider the social implications for local communities. Engage stakeholders in the planning process and address potential impacts on livelihoods, land use, and cultural heritage. Implement best practices to minimize the environmental footprint of renewable energy projects. This includes protecting biodiversity, managing water resources, and mitigating potential negative impacts on ecosystems.

8. Conclusion

In conclusion, transitioning from fossil fuels to renewable energy in the Southern African region is crucial for sustainable development, energy security, and climate change mitigation. Some points noted from the literature are:

- Usage of fossil fuels poses adverse effects like environmental degradation, climate change, and damage to human health among others because of the 89% global greenhouse gas emissions. Economically, this strains economies by increasing fossil fuel subsidies.
- RES like solar PV, wind energy, tidal energy, CSP, and bioenergy are seen to be abundantly available in the Southern African region and some projects have already been successfully implemented especially in South Africa.
- Though there are many benefits for fully transitioning to renewable energies like economic growth and technological advancement, and given the potential that Southern Africa has, exploiting such opportunities remains a challenge due to lack of skilled labor, lack of infrastructure, lack of necessary technology and most importantly, high capital requirements.

The recommendations outlined ranging from policy frameworks and infrastructure enhancement to regional cooperation, investment mobilization, and stakeholder engagement provide a comprehensive roadmap for this transition. Through embracing these strategies, the region can harness its abundant renewable resources, drive economic growth, improve social equity, and contribute significantly to global environmental goals. Future work should focus on refining these approaches through ongoing research, innovation, and the adaptation of best practices to local contexts, ensuring that the benefits of renewable energy are maximized for all stakeholders.

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Author contributions

Anesu Charamba (Investigation [equal], Validation [equal], Writing—original draft [equal], Writing—review & editing [equal]), Hagreaves Kumba (Conceptualization [equal], Formal analysis [equal], Writing—review & editing [equal]), and Denzel Makepa (Conceptualization [equal], Investigation [equal], Writing—review & editing [equal])

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Data availability

All data used in this study are openly available and have been referenced properly.

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