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Renewable energy investments in South Africa: Potentials and challenges for a sustainable transition - *a review*

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Abstract

The Republic of South Africa is one of the leading investors in renewable energy in Africa, despite the widespread perception that the country is trapped in the carbon age due to its high dependence on fossil fuels. Renewable energy, rooted in sustainable development, requires the creation of an appropriate framework and environmentally friendly technologies to support growth. Renewable energy sources are considered more environmentally friendly than fossil fuels, which most energy processes rely on. For this reason, the scope of this article has been narrowed to focus on the motivation for renewable energy and its potential in South Africa. Furthermore, the current developments in the South African renewable energy sector, as well as the challenges and prospects for a sustainable transition to a bioeconomy, were discussed. This study shows that a sustainable energy system can only promote the integration of renewable energy into the energy mix with the help of technology, policy, and infrastructure.

Keywords

Coal, fossil fuel, just energy transition, renewable energy, South Africa

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Introduction

Energy security is becoming increasingly vital and is among the most pressing challenges facing governments worldwide. Burning fossil fuels, including gasoline and diesel, accounts for more than 50% of global primary energy utilisation. The rising price of fossil fuels, combined with the continued prominence of global warming as a major environmental problem, suggests that using substitute fuels is unavoidable in the near future. In general, it is understood that fossil fuels are non-renewable energy sources (REs).[1] South Africa is the highest carbon emitter in Africa, accounting for 40% of the continent's total emissions. It is also one of the most carbon-intensive developing economies in the world, generating 0.6 kg of CO_2 per dollar of GDP. South Africa is one of the most unequal countries in the world. The richest 10% of the population owns 86% of the country's total wealth, over 30% of the population is unemployed, including over 65% of youth, and 55% of the population lives in poverty.[2] The ideal debt-to-GDP ratio is being challenged, growth rates have fallen over the past decade, and the economy is unstable.[3] Against this backdrop, South Africa's response to climate change must promote programs that lead to favourable development outcomes in the context of these issues.

Renewable energy sources (REs), including biofuel, solar, and wind energy, are now a reality, and they are attracting growing interest from the public, investors/businesses, and academia. This is due to a variety of reasons. Still, the most significant are those connected to the volatility of fossil fuel prices, the quest for reduced emissions, and the availability of various energy generation alternatives. Different renewable energies have been investigated for use in transportation, industrial and other sectors. As opposed to gasoline and diesel fuels, all those sustainable energies can be produced from renewable feedstock rather than fossil feedstock. As far as environmental protection is concerned, the major benefit of REs is the ability to allow for a complete carbon cycle to be achieved, which denotes that the plants reabsorb a portion of the CO_2 produced during its manufacture and combustion.[4] The aim of this study is, therefore, to review the viability of RE investments in South Africa. The study attempts to address the following questions:

- What are the potentials of RE in South Africa?
- What is the impact of fossil fuels on the environment?
- What are the current status and challenges of the transition to RE in South Africa?

Why renewable energy: Environmental impact of fossil fuels

Energy plays a vital row in every society for its social and economic development. This implies that for a nation to protect its values, it needs to have well-designed policies and enhanced metrics for energy security. As a developing country, South Africa faces problems like high unemployment rates and extreme inequity among its citizens.[5] The nation aims to transition to a low-carbon future to solve some of these imminent problems. The country's energy-intensive economy relies on low-cost, coal-based electricity to power energy-hungry industries such as mining and metals processing. More than three-quarters of the energy generated in the country comes from fossil fuels,[6] which pose a threat to the

environment due to high CO_2 emissions.[7] South Africa is one of the top ten countries with the highest CO_2 emissions in the world[8] (Figure 1). The government's carbon-based economy has contributed to global warming, escalating the impacts of an overheated climate system, which has led to devastating global climate change.[9]

Consequently, frequent floods and droughts have stricken certain parts of the country for several years, leaving a large population of people vulnerable.[10] South Africa cannot ensure energy security due to the continued rise in global demand for fossil fuels, which is compounded by the country's lack of available oil supplies. This has led to high inflation and provides reasons for a departure from business as usual.[11] Recent price hikes across the globe are partially due to sanctions imposed on Russia after the invasion of Ukraine early in March 2022.[12] Implementing RE will be a viable option to ensure energy security, reduce greenhouse gas emissions, and avoid constant fluctuation of fuel prices.[13]

The South African government targets to shift from carbon-based fuels by 2050 and have 50% of its energy generated from REs.[14] REs are mainly derived from natural resources readily available in the earth's ecosystem. These natural resources are inexhaustible and environmentally friendly. Hence, RE is the best sustainable energy source on the planet.[15] Investment in RE can significantly manage energy-related environmental impacts and reduce the adverse socio-economic problems that arise from fossil energy production and consumption.[16] A recent study by Kumba, Akpan, Twite and Olanrewaju[17] discussed the challenges with the country's major electricity company and affirmed that supporting national policies to aid the shift to RE is pertinent. Thereby, it would significantly aid in increasing South Africa's SDG 7 target, like energy accessibility, beyond the present 85% margin. Hence, energy insecurity can be reduced as well through a reduction in the associated risks and imported fuel costs.

Figure 1. Existing coal-fired power station at Mpumalanga province of South Africa. Pollution from fossil fuel consumption costs South Africans hundreds of billions of rands in public health damage and environmental loss each year (*Sources:* [18,19]).

Potentials of RE in South Africa

The over-reliance on coal, a limited and environmentally damaging resource, can be significantly reduced in South Africa by utilising REs as an alternative energy source.[20] In addition, the growth of the country's RE sector could lead to the creation of more jobs,[21] which would boost the South African economy. South Africa's population and geographical location make the country a significant location for a range of REs, including biomass, wind, and solar energy.

Solar and wind energy

Solar energy is South Africa's most promising REs. The country receives a lot of solar energy due to its geographical location. Most of South Africa has more than 2500 h of sunshine a year, with typical daily solar radiation ranging between 4.5 and 6.5 kWh/m^{2}.[22] Throughout Africa, including the southern part, the sun shines all year round. The annual 24-h solar radiation in South Africa averages around 220 W/m^2 worldwide, compared to an average of around 150 W/m^2 in the USA and around 100 W/m^2 in Europe and the UK. Consequently, South Africa has some of the largest local resources in the world. In South Africa, solar energy is the most easily accessible resource.[23] There are many potential applications, and the market for solar installations in South Africa is growing. The capacity of photovoltaic (PV) panels manufactured annually is 5 MW, and several South African companies manufacture solar water heaters. Numerous devices, including clocks, calculators, stoves, water heaters, lighting, water pumps, communications, transportation, power generation and much more, are powered by solar energy. Like all other REs, solar energy is completely safe and environmentally friendly. Unlike coal-fired power plants, there are no emissions because the fuel source is the sun. Total demand in 2022 was 2.2% (or 5.2 TWh), below the level before the 2019 shutdown. Demand was similar to 2021.[20]

Another important potential source of RE is wind energy. It is estimated that South Africa's total wind power potential is 6,7000 GW, which rivals its solar potential. Since the early 1990's, about 30,000 wind turbines have been installed in the arid and agricultural regions of South Africa to supply water for domestic and agricultural use, while the commercial use of wind energy for electricity generation has not yet received much attention.[24] According to the analysis of the study by Akinbami, Oke and Bodunrin,[20] South Africa could utilise about 6 GW of wind energy under modest assumptions, and this amount could exceed 50 GW. To increase sustainability and diversify the country's energy sources, the South African government, the Department of Energy and the National Energy Regulator of South Africa have created policies and programs for the purchase and use of RE to supplement their fossil fuel production. Over 92 power producers can feed more than 6300 MW of electricity into the grid under the Renewable Energy Independent Power Producers Procurement Program (REIPPPP), primarily from solar and wind energy. The use of green energy has led to lower energy production costs, job creation, foreign investment, and support from regional stakeholders. However, there are still some obstacles to overcome in the integration of this new business sector in South Africa.[25] Coal still dominates the energy mix in South Africa,

accounting for 80% of the system load. In 2022, RE technologies, namely wind, solar photovoltaic (PV) and concentrated solar power (CSP), accounted for 7.3% of the total energy mix with an installed capacity of 6.2 GW.[26] It was the first year in which the output of solar energy (PV and CSP) declined.

There are a number of commercially accessible types of energy storage available today. However, to reduce capital costs and increase the efficiency of energy conversion, new concepts for long and short-term storage are constantly being developed. When used in alternative electricity generation systems (wind, solar or hydropower), RE storage batteries allow energy to be stored when it is available and fed into the grid when needed. The technology known as battery energy storage or battery energy storage systems (BESS) allows energy from REs, such as solar and wind, to be stored and released when it is needed most. Cell phones and electric vehicles use lithium-ion batteries, which are presently the industrial standard for large-scale system storage technologies that help power grids ensure a constant supply of RE.[27]

Energy from biomass

Biomass energy is a sustainable energy source that can be found in solid, liquid or gaseous form and is obtained either directly or indirectly from organic material.[28] According to the South African Renewable Energy Data and Information Service,[20] over 100 GWh of energy was generated from biomass in 2016. No statistics have been kept since then. South Africa has considerable but untapped biomass energy potential. More than 42 million hectares of forest and other crops provide over 1 million tons of wood biomass.[29] The use of biomass in addition to coal can help minimise CO_2 emissions and offset greenhouse gas emissions from coal-fired power plants, as biomass fuel has lower CO_2 emissions and lower sulfur and nitrogen content than coal.[30–32] Since wood, agricultural, and domestic waste that would otherwise have been disposed of in landfills can now be used to generate electricity, co-firing is a useful method of reducing environmental impact. Biofuels are fuels produced from biomass which can be used as transportation fuel or for energy generation; typical examples are bioethanol and biodiesel.[33] Of the fuels produced from biomass worldwide, the United States produces the most, about 46% of global production, while South Africa produces only about 0.3%.[20] The integration of biofuels into the South African energy sector not only contributes to the diversification of fuel sources for energy production but also offers an alternative to the country's continued dependence on crude oil imports for transportation.[34]

With an annual production capacity of over 18 million tons,[35] South Africa is the largest producer of sugarcane on the continent, with bagasse and sugarcane leaves accounting for more than 21% of the total biomass.[20] Unfortunately, the over 1 ton of sugarcane residue that remains is often burnt in the field, and the 2.5 tons of other bagasse produced in the country is also inefficiently burnt. If properly processed, this underutilised biomass could generate over 400 MW of electricity or 1 ton of bioethanol.[20,35] Together with sugar cane, South Africa produces more than 12 million tons of corn annually, with the Free State and Mpumalanga provinces making the largest contribution to this global production.[36] With an annual production of about 5 million tons,

corncobs, or agricultural residues from corn, are among the largest agricultural wastes in the country.[37] With the added benefit of containing less nitrogen and sulfur than coal, corncobs have an energy profile comparable to that of low-grade South African coal.[37,38] Table 1 shows the cost and lifespan comparison between different REs and fossil fuels.

Current state and road map for renewable energy

South Africa has methodically laid the building blocks for economically and environmentally sustainable development and implementation of the future of renewable energies. On the road to a just energy transition, the government plans to meet South Africa's growing energy demand, as outlined in the Just Transition Strategy.

Just energy transition (JET)

In the face of climate change, South Africa's Just Transition strategy aims to ensure a high standard of living for all citizens. The National Just Transition Framework, which was developed as part of a multi-stakeholder engagement led by the Presidential Commission on Climate Change (PCC) and built on the Just Transition clause in Chapter 5 of the National Development Plan of the 2011 White Paper, was recently adopted by the South African government. This framework aims to decarbonise the energy sector and bring about a just transition in the minerals and energy value chains. Although there are different definitions of just transitions in different countries, the National Framework for a Just Transition provides a description that is suitable for the South African context: "*According to the best available research, a just transition aims to provide a good quality of life for all South Africans while promoting resilience to climate change, enhancing the ability to adapt to the adverse impacts of climate change and achieving net zero greenhouse gas emissions by 2050. A just transition creates an environment that is safe for people's health and well-being, affordable, decentralised, diversely owned RE systems, equitable access to water resources, protection of natural resources, and sustainable, equitable and inclusive land use for all, especially the most vulnerable*".[41] The aim of South Africa's Just Energy Transition Investment Plan (JET-IP) is to increase the country's ability to withstand the social, physical, and climatic threats of the transition.

Table 1. Cost and lifespan comparison between different REs and fossil fuel.

Energy Sources	Cost ($/kWh)	Life span (years)	Ref.
Solar PV	0.068	25–40	20
Concentrating solar power	0.18	30	
Offshore wind	0.12	20	
Biomass	0.066	20–30	
Coal energy	0.023	200	39,40

Principles of JET-IP program implementation. The JET-IP proposes the following working definition of a just energy transition for program implementation over the next three to five years, based on the national concept of just energy transition, its principles and priorities:

To achieve the goals of the Nationally Determined Contributions (NDCs), a just energy transition in South Africa creates resilient economies and populations. The methods by which this will be achieved are: (i) developing new, productive models for inclusive economic transitions; (ii) building new, affordable, decentralised and diversely owned RE systems; (ii) supporting diverse affected groups to play an active role in decision-making and implementation of energy transition programs (whether by government or non-government actors); and (iv) restoring ecosystems and natural resources that have been degraded by coal mining and energy production.[41]

In its first five years, the JET-IP has prioritised three sectors: green hydrogen (GH_2), new electric vehicles (NEVs) and electricity. This is a calculated strategic move based on a clear awareness that there are major benefits to be gained from simultaneously unlocking growth in the NEV and GH_2 sectors as the South African energy market decarbonises. Furthermore, the anticipated tax adjustments at the borders of some of South Africa's major trading partners will have a serious impact on South African exports of internal combustion engine (ICE) vehicles and "hard to decarbonise" sectors if action is not taken as soon as possible to reduce emissions in these sectors.[41] Figure 2 presents the current status of JET in South Africa from 2011 to 2023, while the summary of JET-IP investments for the next five years is shown in Figure 3.

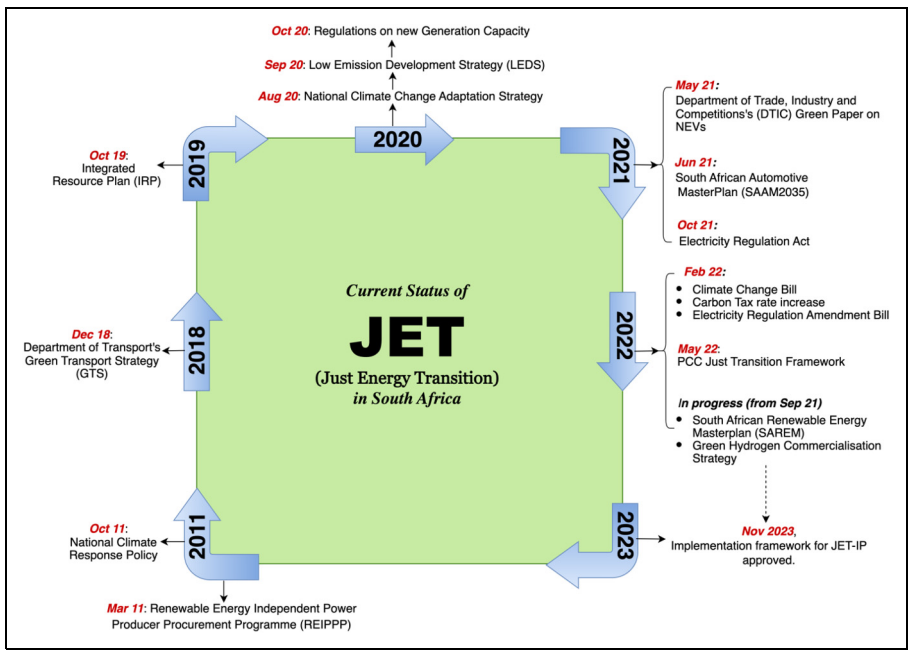

Figure 2. The current status of JET in South Africa (adapted from Ref. 41).

Renewable energy implementation in South Africa

Energy is critical for national development due to the growing industrialisation in the country. South Africa has an estimated 35 billion tons of coal reserves (3% of the total global coal reserves), with 30% export of its coal production, and ranking 7th in the world coal consumption. This implies that the country could use these reserves for the next 200 years at current coal consumption levels, as coal remains a big business in South Africa.[40] Hence, high dependence on coal,[42] as shown in Figure 4(a), has hindered the transition and implementation of REs. Despite this status quo, the South African government's commitments under the Paris Agreement, COP26, and recent energy planning have increased the country's RE efforts. This effort has contributed to the country's diversification to alternative energy sources (nuclear, biofuel, hydropower, solar and wind energy). Incorporating REs in South Africa's energy sector will not only help to diversify the energy sources used to generate electricity but will also ensure energy security by providing an alternative to the country's continued dependence on crude oil imports. With a growing population and developing infrastructure, the country needs to take prudent steps to meet its energy needs for 2020–2050.[27] However, implementation of these REs is still low (Figure 4(b)). The country's policy and regulatory developments are currently helping to refine the existing framework, which focused on RE development, with the progress made on Small-Scale Embedded Generation (SSEG), hydropower policy, the carbon tax, and the enhanced integration of energy efficiency (EE).[43]

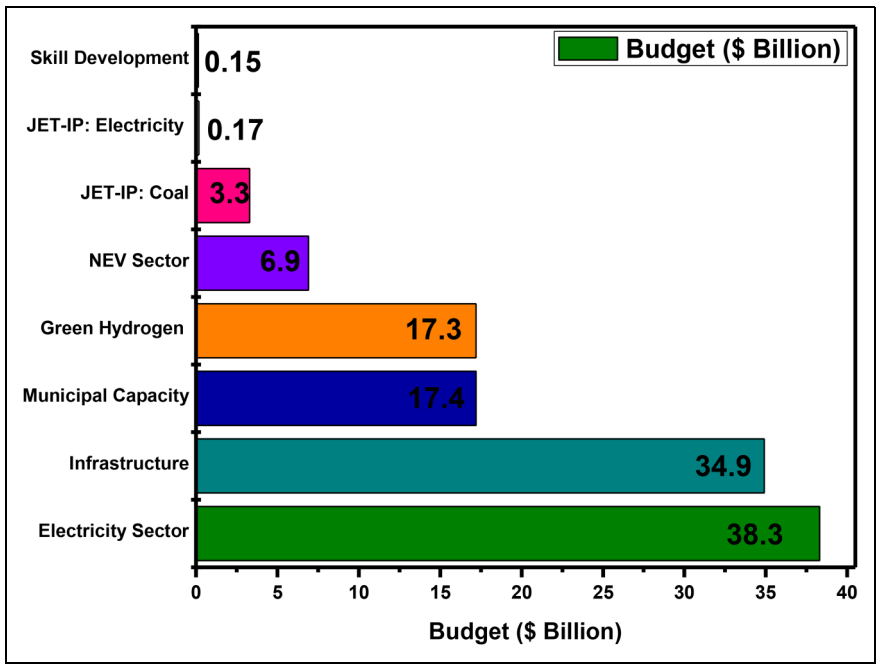

Figure 3. JET-IP portfolio summary of investment needs, 2023–2027 ($Billion) (adapted from Ref. 41).

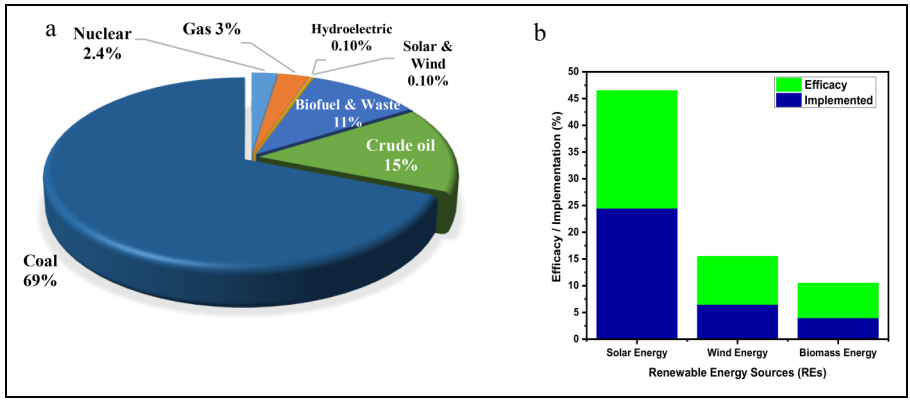

Figure 4. (a) Comparative evaluation of energy supplies in South Africa. (b) Evaluation of the Implementation and Effectiveness of some Renewable Energies in South Africa (*adapted from Uhunamure and Shale*[44]).

Challenges for effective transition to renewable energy in South Africa

Almost half of South Africa's greenhouse gas emissions come from the electrical industry. The country's 39 gigawatts (GW) of coal-fired power plants will be decommissioned over the next three decades, with 22 GW scheduled to close by 2035.[45] As new generation capacity is not being added at the same rate as coal plants are being decommissioned, this has a significant impact on the security of the country's energy supply. In addition, as coal-fired power plants approach the end of their lifespan, they are being used more intensively, increasing the frequency of unplanned outages as there is currently not enough new capacity. These unforeseen interruptions and the lack of spare capacity are currently having a negative impact on the economy. About 90,000 coal workers in the mines and power stations of the impoverished Mpumalanga province, where the sector is concentrated, will be directly affected by the closure of the coal fleet. This will have a catastrophic impact on the many livelihoods sustained by workers in the sector, both in Mpumalanga and nationwide.[46] The impact is even more pronounced at the coal end of the value chain, where coal pollution is found in the manufacturing, transportation, and agricultural sectors, putting the lives of countless more families and communities at risk. For the energy transition to succeed, these societal dangers must be addressed.

High initial capital costs are the most well-known barrier to RE adoption.[47] These costs cater for the initial building and installation of facilities such as solar systems and wind farms. The installation cost for a large-scale solar plant is around $2000 per kilowatt (kW).[48] In contrast, a new fossil fuel-fired power plant costs around $1000 per kW. Therefore, for this reason, investors are more prone to see renewables as high-risk, whereas they find fossil fuel-based power plants more economical due to their low installation costs. Another challenge for effective RE development is the lack of infrastructure. The current electrical infrastructure was built mainly for conventional power

plants, and this gives problems for renewable systems not located near the existing infrastructure. Therefore, to effectively develop renewable systems, a new transmission infrastructure is needed. Non-renewable energy systems are well established, and they hold a big share in the current energy market.[49] Indeed, this is another challenge for RE development. Several countries are still having policies and regulations developed around monopoly providers. These policies support the dominant energy production systems and make it difficult for RE to penetrate the market share. Thus, an amendment to existing policies and regulations is needed to develop RE systems effectively.

Key to note also is that affordability plays a critical role in the country's energy options. With vast amounts of coal reserves, making up 7% of the world's total,[50] the government has a constrained appetite to adopt more expensive options like solar, wind, hydro and biofuel. As also highlighted, legacy energy production infrastructure militates against the incentive to adopt RE options as the government seems to lag in investing in new tech-driven facilities required for RE production.[51] For instance, this is true in wind energy, which is hampered by farm location. Akinbami, Oke and Bodunrin[20] indicated that most wind farms in South Africa are often in remote areas, making a connection to the grid challenging. This implies that in the absence of modern grid infrastructure, most of the power generated will be lost.[52] Akinbami, Oke and Bodunrin[20] also contended that, among other reasons, land and water scarcity have a significant impact on RE adoption in the country. The study charged that the push to promote biofuel usage has created an unintended dilemma of competition between food security and biofuel production. This was also supported by Rulli, Bellomi, Cazzoli, De Carolis and D'Odorico,[53] asserting that in 2013, crops that could have been utilised to feed at least 280 million were used for biofuel production. Some recent studies, though contested, have since attributed the cost of food in South Africa to the growth in biofuel production.[54] This shows the delicacy of this subject, especially in developing countries where poverty remains the biggest challenge. Finally, these challenges are worsened by the country's somnolent RE policy framework. Akinbami, Oke and Bodunrin[20] reported that the country's approach to including RE in the energy mix is fragmented and lacks the necessary support to promote the growth of RE use in the country.

Prospects for a successful transition to renewable energy

Effective RE development can ensure energy access to facilities and households disconnected from the main national electrical grid. The robust flexibility of RE can serve as the backbone of a decentralised national electrical grid.[25] With the emergence of a fourth industrial revolution that has come with edge advancements on the Internet of Things (IoT), Artificial Intelligence (AI) and Web 3.0 are starting to gain momentum. A decentralised national electrical grid that runs on blockchain technology can serve as the best antidote for most third-world countries to solve rampant corruption in government offices and facilitate faster adoption of a low carbon footprint society by the mass population.[55] Adopting these new technologies can increase public participation in RE distribution in a way that can solve many social and economic problems like inequality, unemployment and poverty.[56] This could ensure that everyone can access "green" sustainable energy

at an affordable price. The transport sector in the country is still dominated by vehicles that run on fossil fuels at the expense of the environment. Prompt adoption of electric vehicles can reduce the excessive dumping of CO_2 into the atmosphere, one of the greenhouse gases accelerating global climate change.[57] Both battery electric vehicles (BEV) and hydrogen fuel cell vehicles (HFCV) are viable in South Africa as the country already mines and produces the most important minerals used in battery-powered vehicles like nickel, lithium, cobalt, and platinum, that is also used in HFCV. The abundance of RE in the country could be an economic opportunity for research and development that can foster new industries that will further diversify the economy. The cost of energy production using photovoltaic (PV) has come down to an all-time low. This has allowed photovoltaic solar cells to be widely adopted.[58] The theoretical potential for photovoltaic-generated energy in South Africa is enormous because the country receives about 220 W/m^2 of solar radiation per day and sunshine all year round.[20] Implementing solar photovoltaics with a decentralised electrical grid that runs on blockchain technology can enable quick adoption of RE and solve most of the current environmental and economic problems facing the country.

Some RE technologies such as hydropower, geothermal energy, biomass energy, solar energy, wind energy and biofuels are currently being used, while marine energy, concentrated solar photovoltaics (CSP), enhanced geothermal energy (EGE), cellulosic ethanol, artificial photosynthesis (AP) and many others are examples of these emerging sustainable technologies.[59] Each of the newly developed RE technologies is very promising and has shown that it is possible to meet humanity's energy needs on Earth sustainably. Within each of the primary developing technologies, there are still sub-technologies. Some of the many technologies that comprise the developing renewables are already close to grid parity and are beginning to penetrate the market. Although some of these technologies are still a long way from becoming mainstream, they could be of great benefit to sustainable energy supply in the future. Furthermore, all of these technologies are developing faster than ever before.[59] Figure 5 shows the strengths, opportunities, weaknesses, and threats (SWOT) matrix of RE investment in South Africa.

Conclusion and recommendation

This study focused on RE investments by reviewing the potential of the predominant REs in South Africa, including wind, solar and biomass. The development and use of REs can make a significant contribution to improving access to electricity and energy in South Africa. What is needed is the development of appropriate policies and initiatives to encourage investment from all sources to harness these natural resources fully. Consequently, effective collaboration between the South African government and key energy stakeholders is required to address and resolve these challenges in the development and implementation of RE.

Although South Africa has enormous potential for biomass, wind and solar energy, its main fuel source is coal, which is cheap but not economically friendly. The country's over-reliance on coal is putting a strain on its current coal-fired power plants, so the development of REs is crucial. Based on the findings of the study, the JET Implementation Plan will be a collection of best practices aimed at achieving a long-term transition to

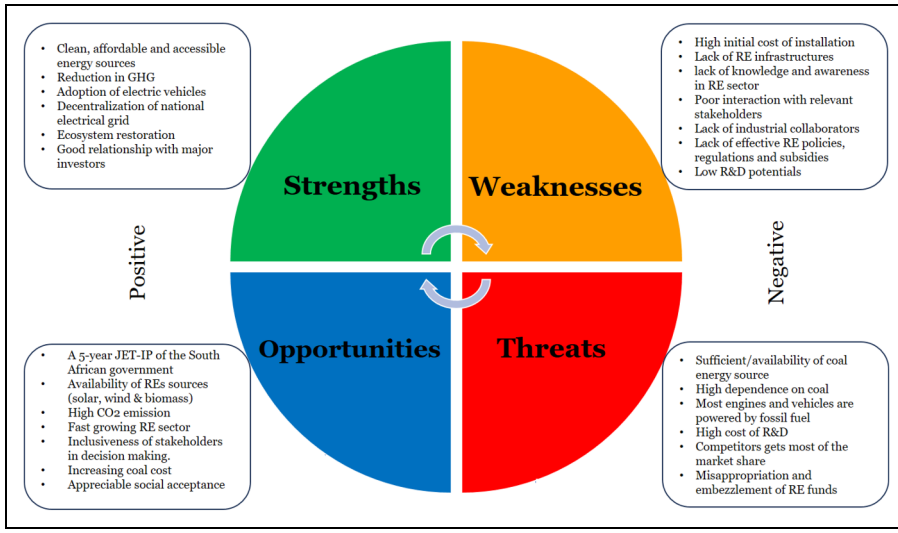

Figure 5. SWOT matrix of RE investment in South Africa.

renewable energy sources, including initiatives by government, civil society, labour unions and the corporate sector. It will also utilise relevant timelines and strengthen existing processes and institutions in South Africa by adopting regional and global best practices in a variety of areas.

There are several obstacles to the growth of RE in the nation, even if direct normal irradiance (DNI), wind speed, and the amount of biomass produced annually are sufficient to harness solar, wind, and biomass energy in the nation. These difficulties are financial, political, technological, and environmental. Some recommendations are made to mitigate these difficulties and thus improve the inclusion of REs in South Africa's energy mix. These recommendations are:

- To efficiently collect and recycle more household waste and agricultural residues, an effective waste management program should be offered, especially in rural or previously unserved areas. These wastes have the potential to be productive sources of biomass energy, especially when combined with coal in current coal-fired power plants.
- An environment conducive to investment should be provided. This can take the form of loans, subsidies or even legislation to encourage the expansion of the RE sector. Policies should be implemented only after they are envisioned. As these policies are not being implemented, certain current policies have failed to solve the problems they were intended for.
- With South Africa's domestic sector consuming more than 23% of the energy generated annually,[60] the use of such technology would significantly contribute to reducing the country's over-reliance on coal, ultimately leading to a reduction in CO_2

emissions. The benefits of RE for society, especially in rural areas, should also be publicised.

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References

1. Anekwe IMS, Khotseng L and Isa YM. The place of biofuel in sustainable living; prospects and challenges. In: *Reference module in earth systems and environmental sciences*. Amsterdam: Elsevier, 2021, pp.226–258.
2. Stats S. *Quarterly Labour Force Survey (QLFS) Q1*. Pretoria: Department of Statistics, South Africa, 2022. https://www.statssa.gov.za/publications/P0211Presentation%20QLFS%20Q1%202022.pdf.
3. *National Treasury, Republic of South Africa*. *Budget Review 2022*. Pretoria: Department of National Treasury, South Africa, 2022. https://www.treasury.gov.za/documents/national%20budget/2022/reviewPrelims.pdf.
4. Gerbrandt K, Chu PL, Simmonds A, et al. Life cycle assessment of lignocellulosic ethanol: a review of key factors and methods affecting calculated GHG emissions and energy use. *Curr Opin Biotechnol* 2016; 38: 63–70.
5. Banks JA. *Diversity and citizenship education: Global perspectives*. San Francisco, CA: John Wiley & Sons, 2006.
6. Pegels A. Renewable energy in South Africa: potentials, barriers and options for support. *Energy Policy* 2010; 38: 4945–4954.
7. Coccia M. New directions of technologies pointing the way to a sustainable global society. *Sustain Futures* 2023; 5: 100114.
8. Ahmad M and Khattak SI. Is aggregate domestic consumption spending (ADCS) per capita determining CO2 emissions in South Africa? A new perspective. *Environ Resour Econ* 2020; 75: 529–552.
9. Winkler H. Climate change and developing countries. *S Afr J Sci* 2005; 101: 355–364.
10. Orimoloye IR, Belle JA, Orimoloye YM, et al. Drought: a common environmental disaster. *Atmosphere (Basel)* 2022; 13: 111.
11. Walwyn DR and Brent AC. Renewable energy gathers steam in South Africa. *Renewable Sustainable Energy Rev* 2015; 41: 390–401.

12. Mbah RE and Wasum DF. Russian-Ukraine 2022 war: a review of the economic impact of Russian-Ukraine crisis on the USA, UK, Canada, and Europe. *Adv Soc Sci Res J* 2022; 9: 144–153.
13. Akpasi SO and Isa YM. Review of carbon capture and methane production from carbon dioxide. *Atmosphere (Basel)* 2022; 13: 1958.
14. Shouman ER. International and national renewable energy for electricity with optimal cost effective for electricity in Egypt. *Renewable Sustainable Energy Rev* 2017; 77: 916–923.
15. Saidi K and Ben Mbarek M. Nuclear energy, renewable energy, CO2 emissions, and economic growth for nine developed countries: evidence from panel granger causality tests. *Prog Nucl Energy* 2016; 88: 364–374.
16. Al-Shetwi AQ. Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges. *Sci Total Environ* 2022; 822: 153645.
17. Kumba H, Akpan J, Twite B, et al. *Renewable energy adoption and integration in South Africa: an overview*. Xiamen: Institution of Engineering and Technology, 2023.
18. *Carbon Brief*. The Carbon Brief Profile: South Africa. Accessed 29 March 2022., https://www.carbonbrief.org/the-carbon-brief-profile-south-africa
19. *Centre for Environmental Rights*. Environmental Justice Organization condemn SA's plans for more coal electricity. Accessed 26 March 2022, https://cer.org.za/news/environmental-justice-organisations-condemn-sas-plans-for-more-coal-electricity
20. Akinbami OM, Oke SR and Bodunrin MO. The state of renewable energy development in South Africa: an overview. *Alexandria Eng J* 2021; 60: 5077–5093.
21. Chetty K, Davids YD, Kanyane M, et al. Fostering a just energy transition: lessons from South Africa's renewable energy independent power producer procurement programme. *S Afr J Int Aff* 2023; 30: 225–244.
22. Xaba N. Whose just energy transition? A South African perspective. *Wiley Interdiscip Rev Energy Environ* 2023; 12: e478.
23. Abdelrazik MK, Abdelaziz SE, Hassan MF, et al. Climate action: prospects of solar energy in Africa. *Energy Rep* 2022; 8: 11363–11377.
24. Asamoah J. *Greening electricity generation in South Africa through wind energy*. Amsterdam: Elsevier; 2003: pp. 1349–1352.
25. Jain S and Jain PK. The rise of renewable energy implementation in South Africa. *Energy Procedia* 2017; 143: 721–726.
26. Ahmad M and Zeeshan M. Validation of weather reanalysis datasets and geospatial and techno-economic viability and potential assessment of concentrated solar power plants. *Energy Convers Manage* 2022; 256: 115366.
27. Akom K, Shongwe T and Joseph MK. South Africa's integrated energy planning framework, 2015-2050. *J Energy South Afr* 2021; 32: 68–82.
28. Sanderson MA, Adler P and Martin NP. Biomass, energy, and industrial uses of forages. In: *Forages: The Science of Grassland Agriculture* 2020; vol. 2: pp. 789–799.
29. Petrie B and Macqueen D. *South African biomass energy: little heeded but much needed*. London: IIED Briefing Paper-International Institute for Environment and Development; 2013.
30. Prins M, Ptasinski K and Janssen F. From coal to biomass gasification: comparison of thermodynamic efficiency. *Energy* 2007; 32: 1248–1259.
31. Hughes E. Biomass cofiring: economics, policy and opportunities. *Biomass Bioenergy* 2000; 19: 457–465.
32. Ren X, Sun R, Meng X, et al. Carbon, sulfur and nitrogen oxide emissions from combustion of pulverized raw and torrefied biomass. *Fuel* 2017; 188: 310–323.
33. Anekwe IMS and Isa YM. Catalytic conversion of low alcohol to hydrocarbons: challenges, prospects, and future work considerations. *Int J Energy Res* 2023; 2023: 1648449.

34. Dong K, Yang S, Wang J, et al. Revisiting energy justice: is renewable energy technology innovation a tool for realizing a just energy system? *Energy Policy* 2023; 183: 113820.
35. Mandegari M, Petersen AM, Benjamin Y, et al. Sugarcane biofuel production in South Africa, Guatemala, the Philippines, Argentina, Vietnam, Cuba, and Sri Lanka. In: *Sugarcane biofuels: status, potential, and prospects of the sweet crop to fuel the world*. Cham: Springer, 2019, pp.319–346.
36. Wettstein S, Scharfy D, von Blottnitz H, Mitigating environmental impacts from agriculture in emerging economies: a case study of solar powered irrigation in the South African maize production. 5th International EcoSummit Congress, EcoSummit 2016 Conference proceedings, Montpellier, France.
37. Danje S. *Fast pyrolysis of corn residues for energy production*. Stellenbosch: Stellenbosch University, 2011.
38. Mohlala LM, Bodunrin MO, Awosusi AA, et al. Beneficiation of corncob and sugarcane bagasse for energy generation and materials development in Nigeria and South Africa: a short overview. *Alexandria Eng J* 2016; 55: 3025–3036.
39. Edkins M, Marquard A and Winkler H. *South Africa's renewable energy policy roadmaps*. Amsterdam: Energy Research Centre, University of Cape Town, 2010.
40. *Eskom*. *Coal in South Africa*. Pretoria: Generation Communication, South Africa, 2021. Accessed 25 December 2023. https://www.eskom.co.za/wp-content/uploads/2021/08/CO-0007-Coal-in-SA-Rev-16.pdf.
41. *Presidential Climate Commission*. *Laying the foundation for a just transition framework for South Africa*. Pretoria: Presidential Climate Commission, 2021.
42. Lenferna A. South Africa's unjust climate reparations: a critique of the just energy transition partnership. *Rev Afr Polit Econ* 2023; 50: 491–501.
43. *Department of Energy*. *State of Renewable Energy in South Africa*. Pretoria: Department of Energy, South Africa, 2017. Accessed 21 March 2022. http://www.energy.gov.za/files/media/Pub/2017-State-of-Renewable-Energy-in-South-Africa.pdf.
44. Uhunamure SE and Shale K. A SWOT analysis approach for a sustainable transition to renewable energy in South Africa. *Sustainability* 2021; 13: 3933.
45. *Eskom*. *Integrated Report 2022*. Pretoria: Department of National Treasury, South Africa, 2022. https://www.eskom.co.za/wp-content/uploads/2022/12/2022_integrated_report.pdf.
46. Makgetla N and Patel M. *The coal value chain in South Africa*. Pretoria: Trade & Industrial Policy Strategies, 2021.
47. Ugulu AI. Barriers and motivations for solar photovoltaic (PV) adoption in urban Nigeria. *Int J Sustain Energy Plan Manag* 2019; 21: 19–34.
48. DiOrio NA, Freeman JM and Blair NJ. *DC-Connected Solar Plus Storage Modeling for Behind-the-Meter Systems in SAM*. Hawaii: National Renewable Energy Laboratory, 2019.
49. Pursiheimo E, Holttinen H and Koljonen T. Inter-sectoral effects of high renewable energy share in global energy system. *Renew Energy* 2019; 136: 1119–1129.
50. Ndlovu V and Inglesi-Lotz R. Positioning South Africa's energy supply mix internationally: comparative and policy review analysis. *J Energy South Afr* 2019; 30: 14–27.
51. Kime S, Jacome V, Pellow D, et al. Evaluating equity and justice in low-carbon energy transitions. *Environ Res Lett* 2023; 18: 123003.
52. Shejal B and Jamge S. *Wind power stabilization to achieve proper grid connection using power convertor & DSP controller*. Chandigarh: American Institute of Physics; 2010, pp. 147–150.
53. Rulli MC, Bellomi D, Cazzoli A, et al. The water-land-food nexus of first-generation biofuels. *Sci Rep* 2016; 6: 22521.

54. Subramaniam Y, Masron TA and Azman NHN. The impact of biofuels on food security. *Int Econ* 2019; 160: 72–83.
55. Sarkodie SA and Adams S. Renewable energy, nuclear energy, and environmental pollution: accounting for political institutional quality in South Africa. *Sci Total Environ* 2018; 643: 1590–1601.
56. van Niekerk AJ. Inclusive economic sustainability: SDGs and global inequality. *Sustainability* 2020; 12: 5427.
57. Chicco G and Stephenson PM. Effectiveness of setting cumulative carbon dioxide emissions reduction targets. *Energy* 2012; 42: 19–31.
58. Aliyu M, Hassan G, Said SA, et al. A review of solar-powered water pumping systems. *Renewable Sustainable Energy Rev* 2018; 87: 61–76.
59. Hussain A, Arif SM and Aslam M. Emerging renewable and sustainable energy technologies: state of the art. *Renewable Sustainable Energy Rev* 2017; 71: 12–28.
60. Bohlmann JA and Inglesi-Lotz R. Analysing the South African residential sector's energy profile. *Renewable Sustainable Energy Rev* 2018; 96: 240–252.

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