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Towards low-carbon energy state in South Africa: a survey of energy availability and sustainability

Paul A. Adedeji[1,*], Stephen Akinlabi[2], Nkosinathi Madushele[1] and Obafemi O. Olatunji[1]

[1] Department of Mechanical Engineering Science, University of Johannesburg, South Africa.
[2] Department of Mechanical and Industrial Engineering, University of Johannesburg, South Africa.
[2] Department of Mechanical Engineering, Covenant University, Ota Nigeria.

Abstract

The drive towards low-carbon economy in South Africa has necessitated alternative energy sources for electricity generation. More alternative sources have evolved in recent times with a view to making energy available to all and sundry. However, asides proliferation of these sources and extensions in form of micro-grids, the questions of increased availability and sustainability has become a growing concern. This survey investigates the state of the renewable energy system in South Africa with focus on the elements, which enhance energy availability and sustainability in the emerging transition to a low-carbon economy. Case studies of other countries were reviewed and considered in the South African context. It was observed that energy availability on the journey to the low-carbon economy is influenced by physical, climatic, human, prosumer concept and political factors. In sustaining the transition and progressing to a green economy, intelligent use of data from power generation, transmission, and distribution sectors for intelligent data-driven decision-making processes was also found as essential. As part of the sustainability roadmap, efficiency at the end-user side of the value chain and a system thinking paradigm in the harvesting of renewable energy sources (RES) and formulation of supporting policies were also identified. In the overall, the study reveals that South Africa is replete with abundance of RES, however, their continuous availability and sustainability depends on joint interventions of both stakeholders and the government with viable environment for the growth of the sector.

Keywords: Energy availability; energy sustainability; low-carbon state; renewable energy; South Africa

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1. Introduction

About 30 % of the global energy generated is transformed into electricity [1]. However, population increase, economic growth, rural to urban migration and technological development have necessitated increased demand for energy in the form of electricity. International Energy Agency anticipate a 40 % increase in global energy consumption by 2040 [2]. South Africa, as a country has experienced a significant increase in electrification both in the rural and the urban areas from less than 33 % in 1990 to 58 % in 1996 [3,4] and to about 90 % in 2016, success courtesy of government policies and interventions [5]. The country is ranked globally as the seventh largest coal producer with the primary type of coal explored being the bituminous coal [6,7] The abundance of coal in the country has influenced her power sector as South Africa produces about 77 % of its electricity from coal [8]. With the quest

*Corresponding author. Email: pauladedeji2k5@gmail.com

to ensure environmental sustainability and reduced emissions in the country, there is advocacy for the use of mitigation technologies like Flue Gas Desulphurization (FGD) plant in coal-fired power plants [9]. However, the FGD plants only reduces the flue gas emission; they do not eliminate them completely. Despite the country's huge reliance on her coal-fired plants as primary energy sources, it operates one of the highly successful Renewable Energy Independent Power Producer Procurement Programme (REI4P) globally, which has attracted renewable energy (RE) investors [10]. The REI4P established in 2011 [11] was aimed at incorporating more RE generation into the South African energy mix.

RE integration into the energy mix of the country has been systematically viewed as one of the potent means through which the country responds to climate change and energy security [12]. With all the policies developed to favour RE in the country, the question of the country's disposition to effective policy implementation is of high necessity. Notable in the country is the use of RES such as concentrated solar power (CSP), photo-voltaic (PV), wind, hydropower, biomass for power generation [13]. However, integrating more of these sources into the South African energy mix without adequate consideration of their sustainability makes them short-lived. RE projects have taken a good lift in South Africa [14], though more from the standalone perspective. Microgrids are fast springing up with new policies supporting their existence [5,13,15]. However, a cointegration of several RE sources in the national grid and government policies and support schemes to foster their increase and viability in the country need adequate attention.

In the last decade, the implementation of RES as substitutes for non-renewable sources for electricity generation in the country has been on the increase. Eskom, a government-owned electricity manager anticipates a 30 % power generation from CO_2-free sources by 2030 [16]. However, wind, hydropower, PV, biomass and the CSP are still at the infant stage in their exploration for electricity generation in the country compared to the age-long coal fuel. With the integration of RES into the country's energy mix, there is an anticipated increase in the costs of coal-based power generation. This consequentially will increase the financial viability of RE technologies thereby causing a reduction in the power generation subsidy [17].

Mini-grids, microgrids, and small-scale RE projects have lately received preference in their use for electricity generation in South Africa. However, the question of how energy (electricity) sustainability and increased availability can contribute to the low-carbon transition is of keen interest in this study. While this section of the article introduces the topic, section 2 provides the methodology adopted in this survey and gives an overview of the present state of RE and low-carbon economy in South Africa. Section 3 focuses on energy availability and section 4 and 5 focuses on energy sustainability and availability measures respectively. Section 5 concludes the paper.

2. Methodology

In this study, a desktop literature survey was carried out on relevant and recent Scopus indexed articles from reputable journals. Recent reports and bulletins from the South African government and globally recognized energy-related databases were also consulted. Trends in energy-related concepts were identified and case studies of other countries were reviewed and compared with the South African case study. Deductions from these case studies were considered and applied to create a roadmap towards ensuring energy availability and sustainability as the country journey towards low-carbon economy.

2.1. The Present State of RE in South Africa

About six RES have been identified as feasible sources in South Africa. They include; solar, wind, hydropower, biomass, and tidal energy [8]. These identified sources vary in viability from one province to another. Shown in Figure 1 is the historical data of power generation from the three prominent RESs (hydropower, wind and solar) in South Africa collected from the South African Databank† from 1991 to 2015.

From Figure 1, energy from hydropower stations have offered a high prospect over the years. South Africa has three categories of hydropower plants: the run-of-river (Colley Wobbles, First and second falls and Ncora), the conventional reservoirs (Gariep and Vanderkloof) and the pumped hydropower plants (Palmiet and Drakensberg) [18]. In 2012, a gradual increase in the harvesting of other RES (Figure 1) with hydropower contributing the highest (4.211 MWh) was observed. In recent years, more investments have been committed into solar energy harvesting both (PVs and CSPs) [19,20].

In the present-day South Africa, the solar PV, CSP and wind energy resource lead the RE space. At the end of 2018, statistics show that a total of 2,078 MW of wind, 1,479 MW of solar PV, and 400 MW of CSP in South Africa were in operation [21].

† www.statssa.gov.za

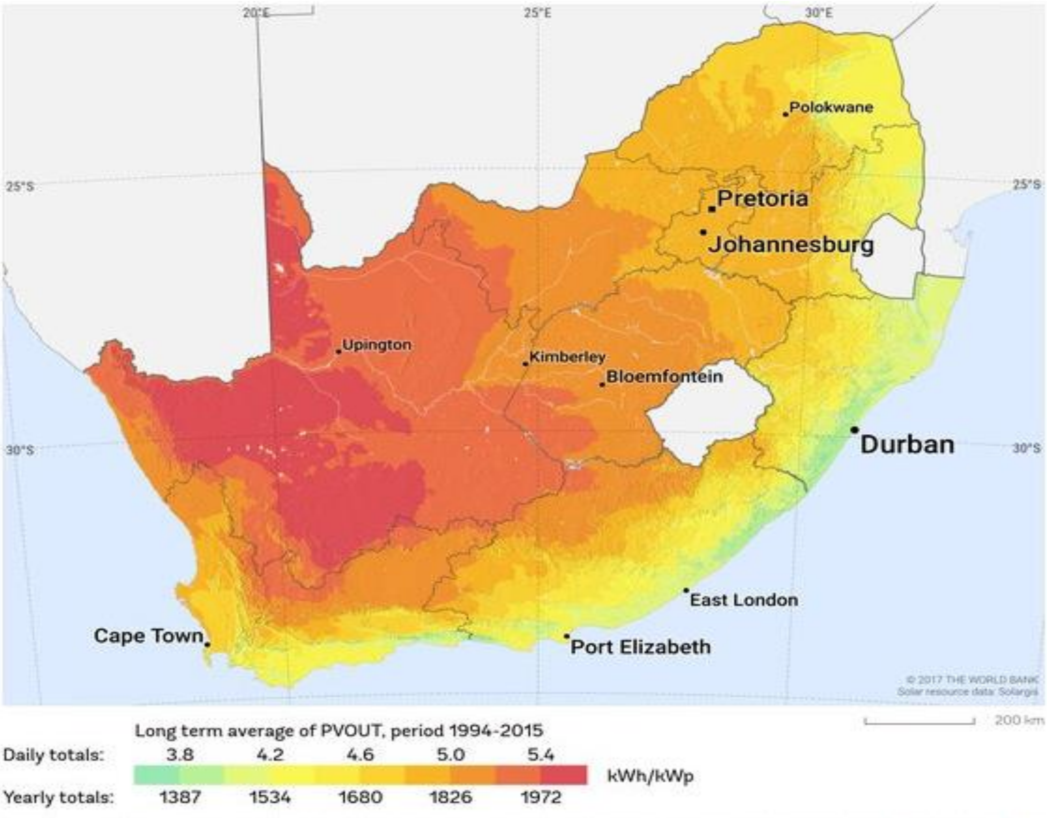

Figure 9. South Africa's photovoltaic resource potential. [54]

Several studies on South Africa renewable energy status has established variation in Solar and Wind energy across the country's nine provinces, which has significant effect on their harnessing for power generation [52,56,57].

c. Human Components

One of the non-deterministic components which affects energy availability is the human component. The human component of the energy sector is a psychological variable, which varies globally from one geographical location to another. The energy sector, regardless of its level of automation, still requires human inputs either at operational, strategic, or administrative level to a certain degree. Decision making, physical monitoring, and facility management are primarily done by humans to a higher degree.

Certain human dynamics affects the productivity of industrial organizations which power generation industries are not exceptions. These dynamics has consequential effects on the energy availability, which could affect productivity and profitability of the system. Some of these dynamics are the personnel's attitude to work and the skillset. Regarding the attitude to work, mental and muscle power is necessary for organisational development; however, the will power has a tendency to overrule these. A study by Surender [58] on the attitude of South African paid workers to work and social grants reveals about 78 % of the paid workers having a notion of hanging on a job even when it is not of your interest. The study was carried out on 39 focus groups in the Eastern Cape and the Western Cape Provinces and comprises a total of 386 respondents. Similar study with a total of 2, 885 South Africans across the nine provinces shows that about two-third of the employed expresses a level of satisfaction with their job, however, Black African workers remained less satisfied with their jobs than their white counterparts [59,60]. Mncwango [59] stated that job satisfaction, measured in terms of tends to increase with age, social status and the level of education and a higher degree of job satisfaction is noticed in the men than in the women. Since job satisfaction is directly proportion to productivity, an unsatisfied workforce is most likely to negatively affect the energy system in terms of availability with a ripple effect on the country's economy.

In term of skill, even though the country is increasingly developing local citizens in the renewable energy industry, the absence of enough manpower with requisite skills in the renewable energy space who can take up the upcoming energy challenge is still prevalent. Although South African Renewable Energy Technology Centre (SARETEC) is taking the lead in this regard, there are still so much to be done. The institution is immensely contributing to the growth of RE in the country by providing requisite industrial skills to participants specifically in the solar and wind energy space, however, the cost of training is considered significantly high for many citizens and participation in the trainings often requires a sponsorship for students. To foster energy availability in the country in the coming energy transition, there is need for local competent personnel with necessary skills in the supply chain of RES from cradle to grave. This would reduce the overhead cost and in turn could reduce the electricity tariff but most importantly increase system availability.

d. Prosumer concept and policy

The prosumer concept represents the dual nature of energy consumers not only consuming but also producing even if it is in micro-scale. It is obvious from Figure 2 that every province in South Africa has one or more renewable energy resources which can be harnessed in small or large scale. The use of solar powered heaters not only reduces energy consumption from the grid in its use but also reduces cost of energy on the part of its users. Availability of biomass feedstock in all provinces is established [19] even though this may not be available on a commercial scale across all provinces. Small-scale bio-digesters in homes reduces electricity cost expended on space heating and cooking. However, the efficiency of the prosumer concept lies on supporting government policies. Gleaning from prosumer schemes from other countries, we considered a study by Inderberg et al. [61] conducted on Norway, Germany, and the United Kingdom (UK). The study investigated the vital factors that increase the number of prosumers in the energy sector. The study investigates direct regulatory provisions, support schemes and the third-party installer markets. While the introduction of third-party installation markets in all the three countries increased the numbers of prosumers, this factor was observed to be dependent on support schemes. The number of prosumers was observed to increase in economies ardently in need of decarbonization as in the case of Germany and the UK. Regulatory factors in the form of licenses, pricing, was observed to also depend on support schemes from each of the countries. Adequate support schemes which fosters prosumerism could be adopted in the South African case study, thus increasing the level of decarbonization and energy availability. Small-scale embedded generation is encouraged by the country since the relaxing of the Electricity Regulation Act in the year 2007, which allows feed-in to the grid [62]. However, policies which accrues incentives to small-scale embedded generation has great prospects on the journey to the low carbon state. By this, manufacturing industries will not only experience reduction in their carbon footprints but also cut down on their carbon tax bills at the end of each fiscal year.

The prosumer business models are hinged on five (5) categorical key principles as identified by Brown et al. [63]. These include; the customer interface (customer's integration in the model design phase), value proposition (service delivery across multiple energy vectors can increase higher value creation and capturing), the supply chain (prosumer business models must positively improve existing energy value chain as it still depends on it despites its high level of decentralization), financial model (revenue increase for new prosumer models can be achieved by: increase in self-consumption behind the meter; price improvement on exported power; ensuring litheness, balance and improvement in ancillary service market; a shift in energy vectors asides electricity) and governance (explicitness of government policies on energy). More on these principles can be found in [63].

e. Political Factors

The political factor forms one of the major key issues in the energy sector and significantly determines both energy availability and sustainability. Reform, policy adoption, and bills are positively related to each political era and so can be drivers or barriers to energy availability. Energy reforms and policies on energy access is more likely to be risky in a country with one-party rule or a limited electoral competition [64–66]. In the energy sector, the organisational structure of regulatory bodies and the degree of autonomy of elected political institutions influences the degree of regulatory risks and existing policies [67]. This is because increased autonomy among regulators may likely resist political pressures. It was argued by de Jongh [68] that clear and favourable political climate in the form of clear policies and well-defined RE objectives predicates the viability of RE investments. The South African government energy policy as stated in the 1998 [69] and 2003 [17] white papers from the Department of Minerals and Energy, was geared towards the following: (a) increased access to affordable energy services (b) fostering economic development (c) managing environmental impacts associated with the energy sector (d) improvement on energy governance (e) energy security through diversification of sources. With this in place, the country has been on the train by encouraging renewable energy integration into the country's energy mainstream. The post-apartheid era in South Africa gave an emergence to the country's Renewable Energy Independent Power Procurement Programme (REI4P) aimed at installing 17.8GW electrical power into the country's mainstream using RES comprising the wind, solar, biomass, hydropower, and biogas by 2030 [14]. While gradually planning to phase-off the coal power plant [7], it is anticipated that jobs will be lost from the present coal plants during the transition. The present unemployment rate in the country stands at 25 % with the economic development plan aiming at about 300,000 jobs to be created in the green economy [70]. Creation of more jobs and retention of the existing jobs have been place on priority list of political campaigns [70], hence the reluctance is observed in the phasing-off of ageing coal-fired power plants, which have consequentially affected the transition from the brown economy to the low-carbon economy in the country.

However, the South African National Development plant 2030 (NDP 2030), with employment goals as one of its aims, has favoured governmental support for REI4P. Although the first two rounds of the REI4P have successfully integrated new and smaller companies in the renewable energy space into the power sector, the big renewable energy companies have also benefitted in the subsequent rounds, however, improved policy is highly essential to ensure the relevance of small bidders. This is expected to have impact on the tariff, diversification, and proliferation of renewable sources in the energy mix, thus accelerating the low-carbon transition and increasing energy availability in the country.

4. Energy Sustainability

Sustainability has been defined by World Commission on Environmental Development (WCED) as "Development that meets the need of the present without compromising the ability of the future generations to meet their own needs" [71,72]. Sustainability in energy system is vital to its continuous supply and in turn affects national economy. Energy sustainability is a tripartite concept which includes economic, social and environmental sustainability pillars. This section considers some measures toward ensuring energy sustainability in South Africa relative to the three pillars of sustainability.

4.1 Intelligent data mining and warehousing

Power generation to final consumption by end user produces a large pool of data along the supply chain, which when harnessed makes the system more efficient and reliable. The journey towards low-carbon state requires efficient use of data for system sustainability considering the non-deterministic nature of energy consumption [35,36]. As one of the indices of cyber-physical systems, data mining holds a crucial role in achieving a sustainable RE system [73]. This in turn fosters economic sustainability of the energy system as data-driven decisions can be made for increased profitability across all the tiers involved in the electricity delivery to the end-user. The various data mining techniques functions as either a predictive or descriptive technique as shown in Figure 10 with each technique performing different functions in the process. This survey emphasises the relevance of the predictive model in energy sustainability. We consider the three phases of energy system; the generation, transmission, and distribution and how these three relate to the end user.

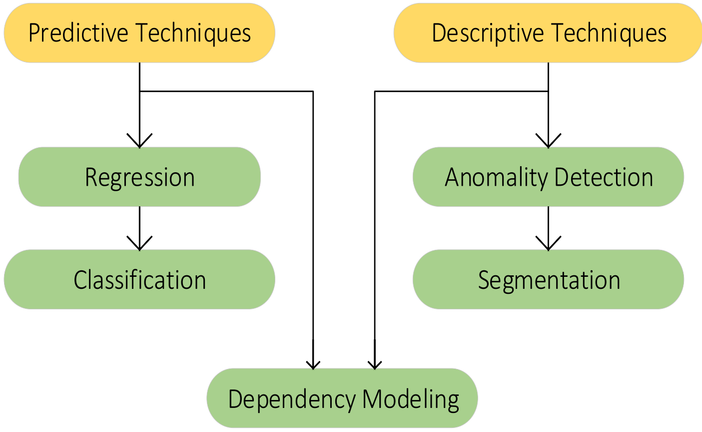

Figure 10. Classification of data mining techniques based on functionality.

4.1.1 Generation

A revolution in power generation system is noticed over the past decade. Power generation plants now operates on Supervisory Control and Data Acquisition (SCADA) system, which gives the state of the system in real time. Condition monitoring, as well as easy troubleshooting, is enhanced with this system put in place [74,75]. Despite a shift to the SCADA system, many power plants only store data acquired on an integrated database without fully harnessing its power at both operational and strategic decision-making levels. In order to enhance sustainability of RES plants, the concept of machine learning to unravel hidden patterns of data must be implemented at the design stage of the plants. A system which reveals the rate of production relative to set daily demand target to be fed into the transmission system is highly essential. The system must be capable of intelligently performing a sensitivity analysis of the effect of increasing generation above threshold on the lifecycle of the plant, both at system and component level. For sustainability, the SCADA system must readily integrate the power plant with data from external environment such that the effect of environmental conditions can be quantified on the system's performance in real time. Integrating weather forecast will foster the efficiency of the plants, to predict when energy is available for transmission unit both at long term and short term. All these capabilities and more are strongly dependent on an efficient and effective data mining system.

In South Africa, data mining and its efficient use on the SCADAs of both independent power producer (IPP) plants and other subsidiary plants offer a great potential in ensuring a reliable electricity. Real-time nowcasting and forecasting can be performed with real-time intelligent condition monitoring and robustness in the operation of generation plants using highly effective artificial intelligent algorithms. Presently in the country, data from generation plants have been under-utilized. Its efficient use will foster economic sustainability in the form of minimization waste in the system, environmental sustainability through reduction in emission as optimal production schedule will be religiously followed, and the social sustainability in the form minimization and maximization of negative and positive impacts respectively on the immediate community.

4.1.2 Transmission

Transmission system connects the generation and the load in an interconnected manner ensuring seamless delivery and enhanced reliability. Renewable energy systems for electricity generation are commonly operated in the form of microgrid, or mini-grid systems; only a few countries run on RES as the major grid. In such case, a nexus of the sources is used. Most often, electricity is transmitted through long distances at high voltage and low current to reduce losses. Data from the transmission system of electricity in terms of losses during transmission to substations and frequency of failures of interconnected grids can be used to redesign the RE system. RES, which are associated with intermittency in harvesting, requires a maximum use of the generated energy, hence losses due to transmission should be grossly reduced. The practice of embedded generation, such that energy is generated close to its point of use is therefore encouraged.

Also, increasing energy sustainability in the power transmission space requires real-time monitoring. Condition monitoring of the transmission lines for on-line fault diagnosis and the monitoring of this echelon in the electricity supply chain is essential. This will require on-line learning of faults and system conditions using intelligent empirical models. The effectiveness of these models is, however, hinged on effective data capturing, processing, storage, and retrieval. Eskom, being the eleventh largest power utility company on the global scale dominates the electricity sector of South Africa generating over 90% of the country's electricity. The company has 26,000 km of transmission lines cutting across the country and extending to most Southern African Development Community (SADC) countries [76]. Integrated data logging on this domain can be useful for condition monitoring to ensure grid stability as well as useful life prediction of infrastructure within the transmission space.

4.1.3 Distribution

Asides minimizing power losses at the distribution phase of electricity, which often results from resistance in electric cables, fraud, instrumental errors [77], an efficient data management system determines the economic viability and technical sustainability of this phase. The electricity distribution network of South Africa is mainly carried out by more than 278 municipalities [78]. These supply electricity to end users, which comprises domestic, industrial, and commercial consumers. Data of who buys what are generated on daily basis from procurement outlets. These data can be harnessed to determine:

i. The number of households that purchased electricity within a specific period.
ii. The number of households connected to the grid and did not purchase between a time frame. This will help to detect leakages, illegal connections, and easy fault tracing, as this is the practice in certain areas.
iii. The consumption in the next fiscal year considering the rate of increase in electrification and buildings. Such data will help to forecast consumptions per sector for strategic planning both for distribution network as well as generation network.
iv. Real time effect of outages from planned and unplanned maintenance and other causes, which can be observed from consumers resistance and complaints.
v. A total quality management system, which entails customer satisfaction, quality of service with six sigma concepts can built from data obtained from this unit.

Electricity sector, like other business enterprises, is established to meet the needs of consumers and make profit in the process. All these at the distribution level enables the electricity sector to remain economically sustainable.

4.2. End-user energy consumption

South Africa has been an energy-intensive country contributes about 1.1 % to the global greenhouse gas emissions and environmental pollution [79]. This effect has been linked to the inefficient use of the energy produced at all strata [80]. It is internationally established that saving a unit of energy is cheaper than producing one unit of energy [62]. Data from end user is relatively out of the loop, however, this can help in building energy efficient devices for end-user community. Data, in the form of energy consumption within a specific time, enables user to plan and optimize budget for same period. Asides the development of smart meters, energy consumption data from end user will help to build more efficient energy optimizer for end users. This can also help to eliminate standby energy consumption from plug load devices.

In the South African case study, many homes in the metropolitan cities have prepaid smart meters installed in their homes except some houses in the townships. The current smart metering in the end-user domain quantifies the real-time energy consumption as calculated from the voltage, phase angle, and frequency in the system. However, smart metering devices capable of bidirectional communication of energy consumption from the user to the supplier with data-logging facilities for user data-driven decision making is essential.

4.3 Systems thinking

Systems thinking emphasizes the nonlinear and dynamic nature of causes and effects [81]. Systems thinking approach enables both policy makers and operational level of decision making to visually consider the bipolar effect of every action. To ensure sustainability of RE system, the concept of systems thinking should be practiced at all levels of energy production from cradle to grave. The energy system is a complex system with several components interacting to produce the behaviour of the system. The complexity of the system increases as the number of components in the system increases. The journey towards low-carbon state entails a hybrid renewable energy system. System thinking considers not only the benefits of these sources but also the disbenefits within the causal loop. It considers the ripple effect of siting RES plants on the biosphere. Conceptualization of a system as holistic analysis and synthesis forms the bedrock of systems thinking [82]. Analysis of component factors involved in RE system, which include the environmental, economic, socio-political, and technical criteria and a synthesis of them all gives a holistic picture of the RE system.

For the South African case study, a critical evaluation of the power sector in its transition to the low-carbon state is highly essential. The question of the effects of the transition to low-carbon economy on other sectors when the country's economy is driven by RE sources requires an honest answer. The pros and cons of this transition should be weighted in a causal loop manner, thus unravelling salient effects likely to erupt over time. Further studies on the renewable energy dynamics of South Africa using systems dynamics approach is greatly encouraged. This will not only unravel latent variables but also improve strategic planning and policy formulation in the energy sector.

5. Conclusions

Low-carbon energy state in South Africa is an achievable feat, however, its realization is hinged on viewing potential alternative energy sources from the standpoint of availability and sustainability. This study has highlighted several factors which contribute to energy availability and sustainability on the journey towards low-carbon economy in South Africa. Renewable power generation on a large scale also involves the tripartite energy phases: generation, transmission, and distribution. A holistic view of the three with a view to harnessing data obtained from each process for strategic and operational planning predicates a sustainable low-carbon South Africa. Consumer efficiency and system thinking concept in energy system fosters the use of scarce energy resources in an efficient manner with an awareness of positive and negative impacts of misuse. On the overall, the peak of energy availability and sustainability in South Africa is an achievable feat, however, its realization is centres around an efficient synergy between all energy components in the energy system dynamics. Integration of artificial intelligence tools in the RE space is open for further research in South Africa. This not only ensures data-driven and informed decision making towards ensuring a low-carbon economy in the country but also a strategic roadmap to a robust and sustainable energy system in the country.

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