



Research Article

Customary land governance and renewable energy integration: Evidence from the Eastern Seaboard smart city project

Lindiwe Ngcobo¹ Silas K. Mulaudzi^{1,2} David Phaho¹

¹ *University of the Witwatersrand, Wits Business School, 2 St Davids Pl, Parktown, Gauteng, 2193, South Africa*

² *South African Local Government Association, Menlyn Corporate Park, 175 Corobay Avenue, Waterkloof Glen, Pretoria*

Abstract

South Africa's transition to low carbon economy requires renewable energy solutions that are responsive to technical, infrastructural, economical and socio institutional realities. This study evaluates the potential for RE integration within the proposed Eastern Seaboard Smart City (ESSC), focusing on the Ray Nkonyeni and King Sabata Dalindyebo local municipalities. A convergent mixed methods case study design was adopted, integrating semi structured interviews with 14 energy sector experts, electricity expenditure data from 36 small businesses, and scenario modelling. Qualitative data were analysed thematically, while descriptive statistics were employed to establish electricity expenditure baseline. Scenario analysis was used to estimate renewable generation, avoided emissions and the gross value of displaced grid electricity. The scenarios evaluated comprised a 138MW wind farm, a 54MW solar plant and a hybrid wind-solar configuration supported by battery energy storage. Assuming capacity factors of 35% for wind and 26% for solar, the modelling indicates annual generation of approximately 423 108 MWh from wind, 122 990 MWh from solar PV and 546 098 MWh from the hybrid configuration. Corresponding annual avoided grid-based emissions are estimated at approximately 398 568, 115 857 and 514 425 tonnes of carbon dioxide equivalent (tCO₂e), respectively. Qualitative findings revealed that RE integration is constrained by inadequate grid infrastructure, financing requirements, regulatory uncertainty, institutional fragmentation and complexities associated with customary land governance. The

study concludes that RE deployment in the ESSC should be approached as a social institutional process, requiring coordinated infrastructure planning, regulatory clarity and meaningful engagement with traditional authorities and local communities.

Keywords: *renewable energy integration, customary land governance, traditional leadership, smart city sustainability*

Received: 16 June 2026

Received in revised form: 16 August 2026

Accepted: 13 September 2026

Published: 19 October 2026

1 Introduction

Poverty remains the major challenge in South Africa. Limpopo, KwaZulu-Natal (KZN), and the Eastern Cape (EC) provinces are the most vulnerable ones based on the Department of Statistics South Africa (StatsSA, 2023). In 2006, Limpopo, exhibited the highest poverty headcount at 75.1%, with KZN and the EC also recording a high headcount of 69.9% and 69.2%, respectively. By 2023, poverty headcount declined, Limpopo was 47.6%, KZN was 49.6% and EC recorded 48.2% (StatsSA, 2023, Table 2.2.1.1). A key contributor to poverty is energy security specifically electricity access. As part of national effort to address this, the South African government launched an Eastern Seaboard smart city project between KZN and the EC (Department of Cooperative Governance and Traditional Affairs (CoGTA, 2025). Despite this positive move, the envisioned city does not have an energy solution framework developed to guide the suitable sources of electricity that will power for this project initiative.

According to the Municipal Infrastructure Support Agent, (MISA, 2023), the ESSC project is located within four district municipalities: Alfred Nzo and O. R Tambo in the EC, as well as Harry Gwala and Ugu in KZN. The pilot phase for smart cities will be in the Ugu District Municipality, specifically in Ray Nkonyeni Local Municipality (RNLM) at Margate, as well as in O.R. Tambo District Municipality at King Sabata Dalindyebo Local Municipality (KSDLM) in Mthatha. The population of KZN was estimated to be 11.5 million, and the EC population was estimated around 6.7 million in 2022, totalling approximately 18.2 million for both provinces (Maluleke, 2022).

Importantly, the ESSC region alone is projected to have over 3.6 million residents out of the population of 18.2 million people of the combined population of KZN and EC that will be impacted by the ESSC project (MISA, 2023). The stability of the electricity grid is crucial for the success of the ESSC development initiative, especially since the region can be classified as rural. Current policies in South Africa need to redefine the importance of electricity by ensuring that it is accessible, affordable, and produced sustainably (Mchunu et al., 2023).

Smart electricity denotes an electricity supply system that employs digital technologies, sensors and two-way communication to monitor, control and optimise electricity flows in real time (Butt et al., 2021; Case Western University, 2024). Integrating Information and Communication Technologies (ICT), the Internet of Things (IoT) and advanced metering enhance the efficiency, reliability and sustainability of electricity generation, distribution

and consumption (Butt et al., 2021; Du Toit & Stimie, 2023). This study therefore evaluates the potential for renewable energy (RE) integration within the proposed ESSC, as an integrated approach in which digital technologies and RE support improved infrastructure management, grid resilience and more sustainable electricity provision (Case Western University, 2024; Du Toit & Stimie, 2023).

The central problem examined in this study is the lack of a sustainable and sufficient electricity infrastructure in the Eastern Seaboard region, where the smart city initiative remains at the planning stage. According to Oke et al. (2020), smart cities depend extensively on reliable, resilient, and RE sources to facilitate technological integration and socio-economic advancement. In this regard, the electricity infrastructural shortfall poses a significant threat to the viability of the ESSC project (Mashau & Kroeze, 2023).

Studies by the Development Bank of Southern Africa (DBSA, 2024), Mashau and Kroeze (2023), Khonjelwayo and Nthakheni (2020), revealed that existing urban settlements in the ESSC region are characterised by ageing, insufficient transformers and substations, which are unable to meet the requirements of a contemporary smart city. These electricity infrastructural challenges hinder the effective distribution of electricity and the integration of RE sources into the main national grid (Du Toit & Stimie, 2023). Furthermore, the lack of robust electricity infrastructure not only affects residential consumers but also impacts businesses that rely on a consistent power supply for their operations (Eastern Cape Department of Economic Development and Environmental Affairs [ECDEDEAT], 2012; Mchunu et al., 2023; Ndubuisi et al., 2025). Consequently, this issue gives rise to several challenges.

Firstly, the inconsistent power supply leads to increased operational costs and reduced productivity for existing businesses, ultimately stifling economic growth and job creation in the region (Khonjelwayo & Nthakheni, 2020). This deficiency not only limits the operational capabilities of current businesses but also deters potential investors from establishing new business opportunities, contributing to a cycle of underdevelopment and diminished opportunities for economic advancement (ECDEDEAT, 2012; Mchunu et al., 2023).

Secondly, energy poverty and high youth unemployment rates are critical challenges exacerbated by unreliable electricity access and affordability issues in some underdeveloped communities (Zondi & Qwabe, 2022). The OR Tambo and Ugu District Municipalities are no exception, where proposed pilot smart cities are to be built. The lack of sufficient electricity infrastructure restricts educational opportunities and skills development programmes essential to preparing youth for the job market (Mashau & Kroeze, 2023).

Thirdly, this situation creates a barrier to economic mobility and perpetuates a cycle of unemployment, and underemployment among young people. Likewise, the lack of a reliable power supply further compounds these problems, as it limits the availability of essential services and opportunities for entrepreneurship, particularly in technology-driven sectors (ECDEDEAT, 2012).

Addressing these interconnected challenges requires the development of smart energy solutions that can enhance the electricity supply and promote sustainable development in the ESSC (Oke et al., 2020). By integrating RE sources and improving infrastructure, it is possible to create a reliable electricity network that meets the needs of local businesses and residents. The study seeks to assess the potential for integrating RE into the ESSC and examining the technical, infrastructural, socio-institutional and socio-economic factors shaping its implementation. This approach not only aims to alleviate energy poverty but also fosters economic growth and job creation, ultimately leading to a more prosperous and

sustainable smart city.

2 Literature Review

2.1 Current electricity infrastructure and usage patterns

2.1.1 Theoretical insights

This study analyses the development and initialisation of sustainable energy infrastructure in South Africa's ESSC initiative through two interconnected theoretical lenses. Thus, Institutional theory (DiMaggio and Powell, 1983), and the Multi-Level Perspective (Geels, 2002). Institutional Theory highlights coercive (e.g. IRP 2025 mandates), mimetic (e.g. Cape Town's solar models), and normative pressure driving legitimacy seeking behaviours amid isomorphism with national frameworks like COGTA's District Development Model. The MLP elucidates niche innovations (e.g. biogas pilots) challenging Eskom's coal regime under landscape pressures like SDG7, potentially destabilising entrenched systems.

2.1.2 Overview of the existing electricity infrastructure in South Africa

In a study by Mashau and Kroeze, (2023) results indicated that rural municipalities in South Africa often have aging and inadequate infrastructure that is ill-equipped to support the development of smart city initiatives. The deployment of smart city technologies requires robust digital infrastructure, including high-speed internet connectivity (Du Toit & Stimie, 2023). However, many small and rural areas in South Africa lack adequate digital infrastructure, hampering the implementation of smart city initiatives (Mashau & Kroeze, 2023). Small and rural municipalities also often have limited budgets, making it challenging to invest in the necessary electricity infrastructure and smart city technologies (Khonjelwayo & Nthakheni, 2020). Developing and managing a smart city infrastructure requires a skilled workforce, which can be difficult to attract and retain in small and rural municipalities, further compounding the challenges faced in implementing smart city projects (Mashau & Kroeze, 2023).

2.1.3 Electricity usage patterns

From a residential perspective, Eskom, (2020) indicated that in South Africa, electricity demand fluctuates based on the time of day, day of the week, and seasons. For, instance, evening peak demand occurs when households simultaneously use appliances for cooking, bathing, and heating in winter. In addition, it is important to note that in the ESSC initiative, development-targeted projects include manufacturing which is high electricity consuming sector (Eskom, 2020; MISA, 2023). According to the Department of Mineral Resources and Energy (2024), South Africa's total energy demand (including electricity) is dominated by the industrial sector (36%), followed by commerce and public services (29%), with transport and residential sectors each comprising 14%, and agriculture and non-specific uses making up the remainder at 2% and 5% respectively. Energy demand per sector is shown in Table 1 below.

Table 1: Energy consumption per sector in South Africa

Sector	Energy Demand (%)
Industrial	36
Commerce and public services	29
Transport	14
Residential	14
Agriculture	2
Non-specific uses	5

Source: DMRE, (2024)

At the national level, South Africa's electricity usage patterns are characterised by various key factors. The country's electricity is primarily generated by Eskom, the state-owned utility, which depends heavily on coal-fired power plants (Moulla et al., 2024). According to the International Trade Administration (2024), Eskom contributes about 95% of the electricity used in South Africa. Electricity usage in South Africa exhibits seasonal variations, with higher demand during the winter season due to increased heating requirements (Eskom, 2020).

A report compiled by the IPP office, (2021) confirmed that the EC province is abundant in wind resources, as a result, it has attracted substantial investment in wind farms like the Nojoli wind farm. History reveals that in 2021, the EC was home to 15 operational wind farms, representing most of the province's electricity demand (IPP Office, 2021). In addition, the Jeffrey's Bay Wind farm, the largest in Sub-Saharan Africa, further solidifies the region's wind power prominence. The province also holds potential for solar energy development. Hydro and biomass exist; however, their development is very limited (IPP Office, 2021).

2.2 Economic, social, and environmental benefits of using renewable energy sources

The adoption of RE technologies in the EC and KZN provinces has the potential to yield a wide array of benefits, spanning economic, social, and environmental dimensions. These benefits can significantly contribute to sustainable development and improve citizens living in these provinces.

Economic benefits

RE offers substantial economic benefits, including job creation, reduced energy costs, and increased energy security. A study by Kumba et al. (2024) stated that the RE sector has the potential to generate a significant number of green jobs, stimulating economic growth and development. Additionally, RE can assist in reducing South Africa's reliance on expensive coal-fired electricity from Eskom, leading to long-term cost savings and enhanced energy security.

Social benefits

Kumba et al. (2024) stated that the social benefits of RE are equally compelling. Improved air quality, resulting from reduced reliance on fossil fuels, can result in public health im-

provements and reduced healthcare costs. Moreover, RE can facilitate access to affordable and reliable electricity for poor communities, particularly in rural areas. The development of the RE sector also necessitates capacity building and skills development, creating opportunities for local communities and contributing to social upliftment (Kumba et al., 2024). Importantly, the Council for Scientific and Industrial Research (CSIR, 2023), added that RE has the potential to address energy poverty and improve the quality of life in rural communities through decentralised energy solutions.

Environmental benefit

RE plays a vital role in environmental conservation and mitigating climate change. By harnessing clean energy sources like solar and wind power, South Africa can reduce its carbon footprint and contribute to global efforts to combat climate change (Kumba et al., 2024). Likewise, RE helps conserve natural resources, such as coal and water, protect ecosystems and biodiversity by minimising the environmental impact associated with fossil fuel extraction and combustion.

3 Methodology

3.1 Research approach and research design

A convergent mixed methods case study design was adopted to investigate RE integration and its socio-economic implications within the ESSC smart city project, incorporating three complementary strands. The qualitative strand comprised 14 semi structured interviews with key experts and stakeholders to obtain insights into RE integration, electricity infrastructure, governance and socio-economic considerations. The quantitative strand analysed electricity expenditure records from 36 small businesses to assess electricity consumption patterns and expenditure. The modelling strand employed scenario analysis using secondary technical and economic parameters to estimate potential renewable electricity generation, avoided emissions and the gross value of displaced grid electricity under alternative RE configurations.

The convergent mixed methods case study design was appropriate because ESSC constitute a geographically bounded, policy relevant development initiative characterised by distinctive institutional and infrastructural and socio-economic conditions. The qualitative component explored stakeholder perspectives on RE opportunities, implementation barriers and governance challenges, while quantitative component established a baseline electricity expenditure among small businesses and developed RE scenarios using secondary technical data from published South African studies. The study therefore aimed to generate context specific evidence to inform RE planning and policy within ESSC.

3.2 Population

The study population comprised key stakeholders directly and indirectly involved in the ESSC project, including representatives from government entities (research and departmental), Independent Power Producers (IPPs), academia, and the private sector industry. Ad-

ditionally, the study targeted small business owners within the pilot municipalities, specifically the Ray Nkonyeni Local Municipality (RNLM) and the King Sabata Dalindyebo (KSDLM).

3.3 Sampling strategy and recruitment criteria

A combination of purposive and snowball sampling was utilised to identify and recruit expert participants. The 14 expert participants were purposively selected based on their professional relevance to RE, electricity infrastructure, municipal governance, energy policy, private sector energy development and related academic expertise. The adequacy of the expert sample was assessed through the recurrence of key themes across the interviews, with saturation considered to have been reached when additional interviews were no longer generating new insights relevant to the research questions. The final sample reflected practical access constraints while maintaining representation of stakeholders with direct knowledge and experience of the energy transition and electricity infrastructure context under investigation. The participant's profiles are shown in Table 2 below.

Table 2: Profile of expert interview participants

Participants ID	Sector	Position	Years of Experience
P1	Private (IPP)	Managing Director	35
P2	Private (IPP)	Managing Director	25
P3	Private (Industry leaders)	Manager	8
P4	Private (Bank)	Principal Specialist	15
P5	Private (Industry leaders)	Director	30
P6	Academia (University)	Associate Professor	19.5
P7	Academia (University)	Executive Professor	18
P8	Academic (University)	Director	29
P9	Public (Research government entity)	Energy Specialist	24
P10	Public (State Owned Company)	Chief Operating Officer	25
P11	Public (Government entity)	Chief Researcher	30
P12	Public (Government entity)	Chief Officer	15
P13	Public (State Owned Company)	Chief Engineer	19
P14	Public (State Owned Company)	Manager	20

Source: Author's own compilation from survey data, (2025)

For quantitative component 18 small businesses in each municipality were recruited directly to provide monthly electricity expenditure data after municipal officials could not share such information due to Protection of Personal Information Act (POPIA). Ethical clearance was granted by the University of the Witwatersrand (ethical protocol number: **WBS/EL2777301/155**) before data collection. Expert interview participation was voluntary, with informed consent obtained prior to interviews. Participant's identities were anonymised using codes. Data were handled confidentially, used solely for research, and complied with applicable data protection requirements.

Government entities were selected due to their responsibility for service delivery and their practical understanding of community-based projects. Government research institutions play a crucial role by contributing valuable data derived from nationwide feasibility studies. The private sector was selected owing to its significant influence within the South African energy landscape, offering critical insights into the financial and technological viability of

energy projects. Independent power producers (IPPs) were also included, recognising their essential involvement in energy generation and project implementation.

3.4 Data collection process

Primary data were gathered through semi structured interviews featuring open ended questions, conducted via Microsoft Teams to facilitate in depth insights into the project's challenges and aspirations. Direct consultations were held with small businesses to obtain monthly electricity expenditure. Secondary data were sourced from municipal reports, Eskom records, and established South African studies to gather information on infrastructure, consumption patterns and RE potential.

3.5 Data analysis

Data analysis involved three primary techniques. First, descriptive statistics analysed electricity expenditure data from the thirty-six sampled businesses using averages to establish baseline expenditure patterns within the two pilot municipalities. Second, thematic analysis was applied to interview transcripts. Initial codes were generated inductively and grouped into broader themes relating to RE opportunities, infrastructure challenges, governance, financing, community participation and implementation challenges. Finally, scenario analysis compared alternative energy solutions against financial, environmental and social criteria, linking recurring qualitative patterns to quantified pathways for implementation.

The scenario analysis adopts key clean energy production assumptions and data from locally relevant South African studies to ensure contextual accuracy and applicability. Specifically, the wind energy projections draw upon the life cycle external cost assessment of an onshore wind farm by Ibrahim and Thopil (2025) and the CSIR, 2025 report, while the solar energy estimates reference the 54 MW solar PV plant by Barnard et al. (2021).

3.6 Scenario analysis framework

A scenario analysis was undertaken to examine alternative RE pathways for the proposed ESSC. Scenario analysis is a recognised planning technique that enables comparison of plausible future energy systems under clearly defined technical assumptions, without attempting to predict a single outcome. The analysis combined baseline electricity expenditure data collected from sampled businesses with RE generation parameters reported in published South African studies. Wind energy assumptions were adapted from Ibrahim and Thopil, (2025), while solar photovoltaic assumptions were driven from Barnard et al. (2021). These studies provide context specific estimates appropriate to South African climate, technological and regulatory conditions. RE has the potential to reduce exposure to Eskom tariff escalation and may reduce electricity costs subject to project specific generation, financing and operating costs. Four scenarios were evaluated:

- **Scenario 1:** Continued reliance on Eskom electricity (baseline)
- **Scenario 2:** Integration of a 138 MW wind farm
- **Scenario 3:** Integration of a 54 MW solar photovoltaic plant

- **Scenario 4:** Integration of a hybrid system comprising wind, solar photovoltaic generation and battery storage system (BESS).

The scenarios assume a project lifespan of 20 years. However, electricity generation, displaced electricity, avoided emissions and indicative gross value are reported annually to ensure consistency and comparability across the scenarios.

3.6.1 Scenario analysis calculations

The calculations were undertaken using simple arithmetic based on an assumed annual generation. Summary of all scenarios are presented in Table 3 below.

Table 3: Scenario assumptions

Variable	Wind Scenario	Solar Scenario	Hybrid Scenario
Installed capacity	138 MW	54 MW	192 MW
Project life	20 years	20 years	20 years
Generation estimates	Ibrahim & Thopil, 2025	Barnard et al. 2021	Combined estimates
Storage	None	None	BESS
Purpose	Grid supply	Grid supply	Grid stability and reliability
Capacity factor	35%	26%	Combined scenarios

Source: Author's own computation from published secondary parameters, CSIR, 2025 Ibrahim & Thopil, 2025; Barnard et al. 2021 .

The scenarios were compared using RE generation, implications for grid dependence, anticipated socio-economic benefits and stakeholder assessments of technical feasibility. The scenario analysis is intended to provide indicative comparisons of alternative development pathways rather than project specific financial forecasts.

3.6.2 Level of aggregation

Average annual electricity expenditure

Domestic generation grid emission factor was estimated using 2023 Eskom grid emission factor which was 0.942 tCO₂e/MWh, as identified by the Department of Forestry, Fisheries and Environment (DFFE, 2025), expressed in tonnes of carbon dioxide equivalent per megawatt hour(tCO₂/MWh).

Capacity factor for both wind and solar were sourced from the CSIR (2025) report and Barnard et al. (2021), with the wind capacity factor adapted to 35% and solar capacity factor set at 26%.

The electricity tariff was obtained from RNLM draft 2025/26 electricity tariff schedule where the approved schedule was not available at the time of analysis, the proposed tariff was set at R2.45/kWh (Ray Nkonyeni Local Municipality, 2025).

Localised cost-reduction factor is not included in this study. The scenario analysis estimates the gross value of displaced electricity using the municipal retail tariff but does not model system costs, renewable LCOE, financing, O&M, storage or grid constraints. A defensible cost-reduction factor therefore cannot be calculated from the available parameters without introducing additional assumptions.

3.6.3 Analytical equations

Annual generation

The annual renewable electricity generation was calculated using the standard capacity factor engineering formulation:

$$AG = \text{Installed capacity of a plant (MW)} \times CF \times 8760 \text{ hours/year}$$

Where:

AG = Annual generation

CF = Capacity factor

Displaced Eskom electricity

Potential displacement of Eskom electricity was estimated by assuming renewable electricity generated within the ESSC would substitute an equivalent quantity of grid-supplied electricity.

$$\text{Displaced Eskom electricity} = \text{Renewable energy generated/year}$$

Annual avoided emissions

Annual avoided emissions were estimated by multiplying renewable electricity generation by the South African grid emission factor:

$$\text{Avoided emissions} = \text{Annual renewable electricity generation} \frac{\text{MWH}}{\text{Y}} \times \text{grid factor}$$

The analysis assumes that renewable electricity displaces an equivalent quantity of grid electricity and therefore does not separately deduct emissions from renewable generation. The calculated values represent avoided operational grid emissions, not full life cycle emission.

Indicative gross value of displaced electricity

The gross value of displaced electricity was estimated by multiplying annual renewable generation by the municipal electricity tariff:

$$\begin{aligned} \text{Indicative gross value of displaced electricity} &= \text{Annual renewable generation} \left(\frac{\text{kWh}}{\text{year}} \right) \\ &\times \text{municipal tariff} \times \left(\frac{\text{R}}{\text{kWh}} \right) \end{aligned}$$

Measurement scales and reliability

The trustworthiness of the qualitative data was ensured through prolonged engagement, member checking, and data triangulation across multiple stakeholder groups. Dependability was maintained through transparent documentation of research procedures, while confirmability was supported by an audit trail to mitigate researcher bias. The quantitative data on electricity expenditure served as a descriptive baseline for comparative scenario analysis.

3.7 Study area

The ESSC is a visionary smart city development project in South Africa, aiming to transform a 600-kilometre stretch along the eastern coastline into a dynamic urban area. This initiative spans parts of both the Eastern Cape and KwaZulu-Natal provinces, specifically the districts of Alfred Nzo, OR Tambo, Ugu, and Harry Gwala (MISA, 2023). The Eastern Seaboard region where the ESSC is envisioned is presented in Figure 1 below:

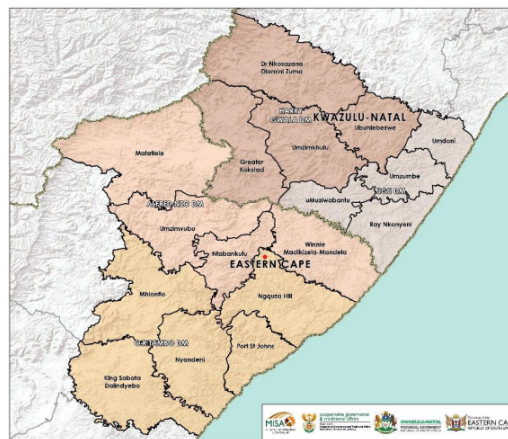


Figure 1: Map showing the Eastern Seaboard region with the study area highlighted in yellow

Source: Municipal Infrastructure Support Agent (MISA, 2023)

4 Results

4.1 Qualitative analysis

4.1.1 Potential for renewable energy sources and their integration into the city's electricity solution

This subsection presents two key themes that emerged from data analysis. The question to be answered in this subsection is “What RE sources can be effectively integrated into the Eastern Seaboard smart city’s electricity infrastructure, and what are the technical and logistical considerations for their implementation?” The first theme is **technological adaptations and resource optimisation**, which includes the sub-themes: diverse RE resources base and need for tailored technological and local adaptation. The second theme is **infrastructure readiness and integration capacity**, which comprises sub-themes related to grid

integration challenges and technical constraints, as well as logistical readiness and sizing specific smart context.

Technological adaptations and resource optimisation

◇ Diverse renewable energy resources

This sub-theme refers to the abundant RE resources available within the region, evaluated in terms of financial, technological, and social feasibility. Participants identified multiple combinations of RE technologies, considering resource availability, seasonal reliability, and the economic viability of each option. Utilising RE in isolation is deemed non-viable, as evidenced by participants proposing hybrid energy combinations instead. This aligns with Tazvinga, Dzobo, and Mapako's (2020) empirical finding that standalone solar photovoltaic system, even during peak production, fail to meet total energy demand due to their daytime only generation window. The proposed combinations are shown in Figure 2 below:

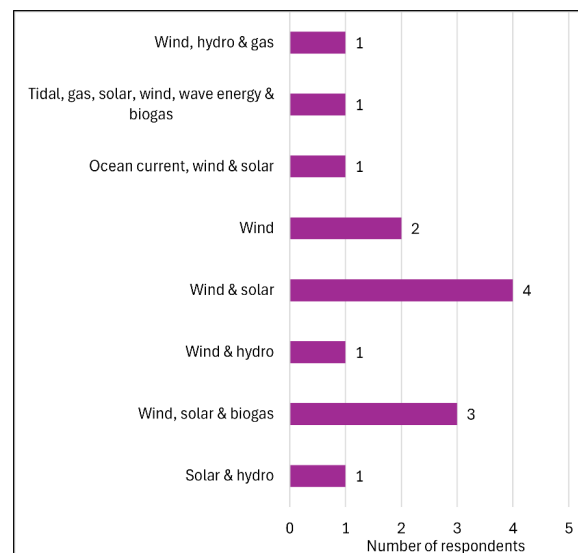


Figure 2: Proposed potential combinations of renewable energy sources in the Eastern Seaboard region

Source: Author's own compilation from survey data, 2025

The results illustrate the distribution of proposed RE combinations for the ESSC. Wind and solar emerged as the most favoured combination, accounting for four of the fourteen responses, followed by wind, solar, and biogas, three of fourteen responses (Fig 2). Wind as a standalone featured among the proposals (two of fourteen responses), highlighting its perceived reliability in the region. The remaining combinations each appeared at a lower frequency (one of fourteen each), including wind and hydro; wind, hydro, and gas; solar and hydro; ocean current, wind, and solar; and a comprehensive combination of tidal, gas, solar, wind, wave energy, and biogas.

Private sector assert that wind and solar are bankable technologies when supported by clear offtake agreements and policy certainty, with resource diversity helping to mitigate weather-related risks and attract investment. They also highlight the opportunity to decentralise generation by leveraging coastal wind and inland solar, reducing transmission losses, and strengthening grid resilience.

Infrastructure readiness and integration capacity

◇ Grid integration challenges and technical constraints

Challenges related to grid integration and technical limitations present major obstacles to the deployment of RE within the ESSC. Academics emphasise that the current electricity grid lacks the capacity to accommodate large-scale RE inputs, citing outdated infrastructure and constrained municipal capabilities as key factors. Without considerable investment, RE projects remain largely theoretical in this context. This perspective is supported by private sector participants, who further identify financial constraints, political interference, regulatory complexities surrounding embedded generation, and maintenance issues as additional barriers to successful grid integration.

The government identified barriers to RE projects that extend beyond technological and financial feasibility. Key challenges include environmental sensitivity, land ownership issues under traditional leadership, grid readiness concerns, and the absence of nearby substations. The challenges related to grid integration and technical support are presented in Figure 3 below:

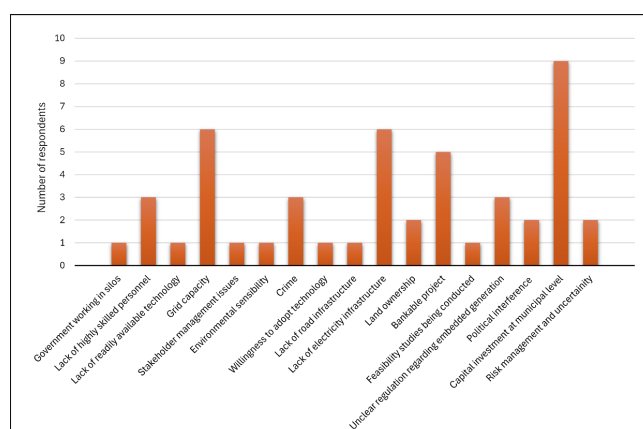


Figure 3: Challenges related to grid integration

Source: Author's own compilation from survey data, 2025

The most frequently cited barrier to RE implementation at the municipal level was the capital investment required, identified by nine of the fourteen participants. This was followed by grid capacity and lack of electricity infrastructure, each mentioned by six participants. The need for bankable projects was identified by five participants (Fig 3). Lack of highly skilled personnel, crime, and unclear regulations regarding embedded generation were each cited by three participants. Land ownership, political interference, and risk management and uncertainty were each identified by two participants.

Government department and institutions working in silos, lack of readily available technology, stakeholder management issues, environmental sensitivity, willingness to adopt technology, lack of road infrastructure, and feasibility studies being conducted were each reported by one participant. Based on the insights presented, the findings demonstrate that RE integration is not determined by technical resource availability alone. In this regard, Institutional Theory helps to explain how regulatory uncertainty, municipal capacity limitations, national policy requirements and traditional authority structures shape the legitimacy and feasibility of RE projects.

◊ **Logistical readiness and sizing for smart city**

Logistical readiness and appropriate project sizing are critical for the successful deployment of RE technologies in the ESSC. Academics highlight that without addressing foundational capacity issues such as municipal contracting mechanisms, local skills, and institutional capacity projects risk inefficiencies and underperformance. They emphasize that smart city success depends not only on technology but also on strong logistical frameworks tailored to regional realities. Government officials add that poor road infrastructure, like the deteriorating N2 through the former Transkei, and the lack of large electricity consumers and accessible land make the region less attractive for investment unless logistics are carefully planned. They emphasise scalable solutions, such as containerised microgrids for rural areas and larger systems for semi-urban zones, aligned with demographic and spatial needs.

IPPs and private sector actors echo these concerns, pointing to logistical bottlenecks like inadequate roads, service infrastructure, and bureaucratic delays that hamper project delivery. IPPs argue for modular, phased project designs that match current and future demand, warning against top-down approaches that overlook local capacity to host and maintain systems.

From a financial perspective, investors require detailed logistics plans covering transportation, warehousing, and local construction capabilities to reduce risks. Misjudging project size either by overbuilding or undersupplying can lead to poor returns. Private participants advocate for integrating digital mapping, resource planning, and local contractor networks to improve alignment. Across all groups, the consensus is that strengthening logistical readiness through coordinated public-private planning and early local engagement is essential to delivering appropriately sized, sustainable energy projects in the ESSC.

4.1.2 Economic, social, and environmental benefits of implementing sustainable clean energy

The calculations of the projected clean energy that can be produced should the ESSC be built and RE be integrated into the main grid are adopted from established South African studies.

◊ **Small businesses' monthly electricity expenditure**

The businesses were categorised into three categories: beauty and cosmetics (saloons), food and beverages (taverns, bars, restaurants, and bakeries), and technology connect, and welding hub (welding, internet cafes, and electronic shops). Results on electricity expenditure in each municipality are presented in Table 4 below.

Table 4: Monthly electricity expenses by small businesses in RNLM & KSDL

	Ray Nkonyeni LM (R)	King Sabata Dalindyebo LM (R)
Saloon 1	850	600
Saloon 2	1400	1200
Saloon 3	1100	950
Bakery 1	2200	1000
Bakery 2	1300	1150
Bakery 3	1800	2100
Restaurant 1	3200	2800
Restaurant 2	2500	2000
Tavern/bar 1	2800	2100
Tavern/bar 2	2000	1600
Electronic shop 1	1200	900
Electronic shop 2	850	700
Electronic shop 3	700	450
Internet cafe 1	2200	1000
Internet cafe 2	1700	1500
Internet cafe 3	1200	900
Welding 1	3000	2500
Welding 2	2200	1800
AVERAGE	R 1 788.89	R 1 402.78

Source: Author's own compilation from survey data, (2025)

Within RNLM, the average monthly electricity expenditure for small businesses surveyed was R 1 788.89 (**R21 466.68** annually), whereas in KSDL, the average was R 1 402.78 (**R16 833.36** annually). The descriptive data indicate that the sampled businesses in RNLM reported a higher average monthly electricity expenditure than those in KSDL. These figures are not intended to represent statistically generalisable differences between the municipalities. Rather, they provide a localised baseline illustrating the electricity cost burden experienced by the sampled SMMEs.

◇ Projected economic benefits of RE integration in ESSC development

The participants were asked to share the economic benefits they anticipate if the ESSC project is successfully implemented. Their responses are summarised in Figure 4 below.

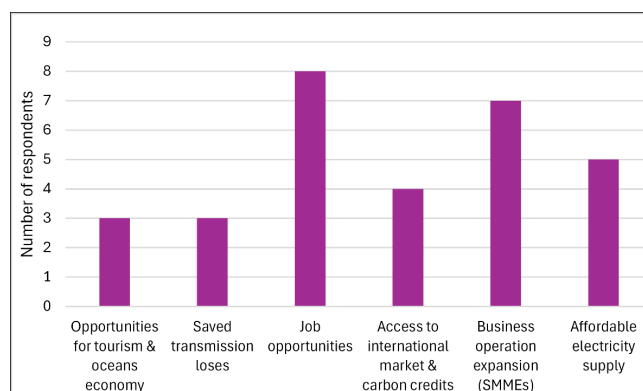


Figure 4: Projected economic benefits by participants

Source: Author's own compilation from data survey, 2025

The highest reported economic benefit of building the smart city in the ESSC was job opportunities, which was mentioned by eight of fourteen participants. This was followed by business operation expansion for SMMEs, highlighted by seven participants. Affordable local electricity supply was noted by five participants while access to international markets and carbon credits was raised by four participants. Tourism and the ocean's economy and saved transmission losses were the least frequently reported benefits. With three participants referring to each of these benefits.

The reduction of transmission losses by generating power locally rather than relying on distant provinces was as beneficial, improving reliability and efficiency. While construction jobs may be temporary, the ethical and transparent implementation of renewable projects is expected to foster sustainable employment in small, medium, and micro enterprises (SMMEs) and the tourism sector. Furthermore, carbon credits and green branding offer new revenue streams that can be reinvested to bolster economic resilience and development.

◇ Projected environmental benefits of RE integration in ESSC development

Participants were asked to indicate the environmental benefits they expect from the successful implementation of the ESSC project. Their responses are presented in Figure 5 below.

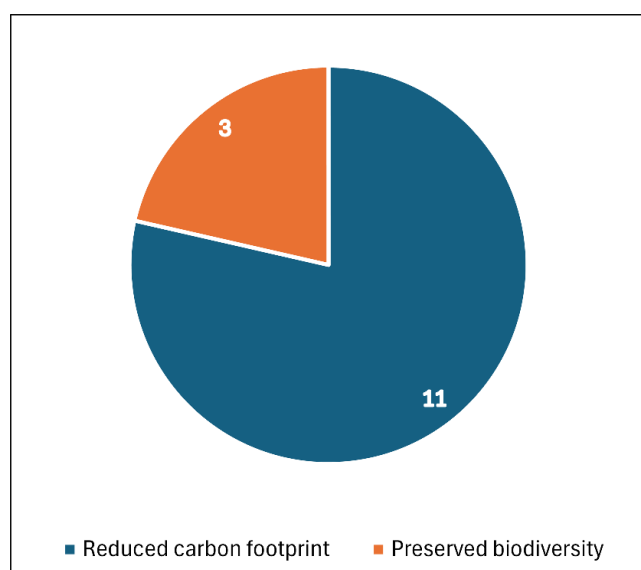


Figure 5: Projected environmental benefits by participant

Source: Author's own compilation from survey data, 2025

The anticipated environmental benefits of integrating RE into the ESSC are significant. Eleven of the fourteen participants identified a reduced carbon footprint as the foremost advantage, reflecting expectations that renewables will displace fossil fuel use and lower greenhouse gas emissions, thereby improving air quality. In addition, three participants highlighted biodiversity preservation, recognising that wind, solar, and small hydro systems cause less ecological disturbance than coal or large hydro projects.

Projected social benefits of RE integration in ESSC development

Participants were requested to outline the anticipated social benefits that would result from the successful implementation of the ESSC project. These benefits are reflected in Figure 6

below.

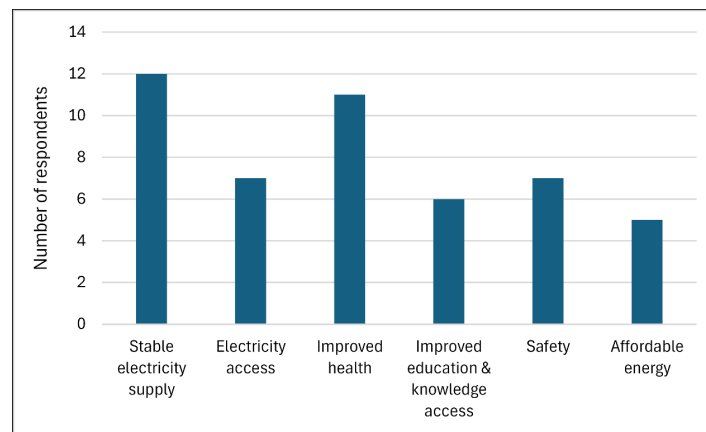


Figure 6: Projected social benefits by participant

Source: Author's own compilation from survey data, 2025

Socially, the integration of renewables promises substantial improvements in quality of life. Stable electricity supply was the most cited benefit (twelve of fourteen participants), understood as uninterrupted 24-hour access free from load shedding and illegal connections, supported by digital fault reporting. Improved health outcomes (eleven of fourteen participants) arise from consistent power enabling hospitals to operate critical equipment and households to safely store medication, while enhanced safety (seven of fourteen participants) is linked to reliable street lighting.

Access to electricity was identified by seven of the fourteen participants as a potential social benefit of integrating RE into the ESSC. This finding suggests that participants believed RE development could extend reliable electricity supply to communities in the region, particularly those experiencing inadequate access. Improved education and knowledge access was identified by six of the fourteen participants as a key benefit, as RE integration enables digital learning, particularly for rural learners. Additionally, five of the fourteen participants noted that RE can improve affordability by reducing electricity costs for households and businesses and limiting their dependence on Eskom's grid supply.

◊ The socio institutional conditions shaping RE integration in the ESSC

The findings show that successful integration of RE into the proposed ESSC depends not only on resource availability and physical infrastructure, but also on a suite of socio institutional factors that shape planning, implementation and long-term viability. Respondents consistently emphasised that RE development in the ESSC is mediated by governance arrangements, institutional coordination, regulatory clarity and stakeholder relations. This implies that the energy transition within ESSC is not merely a technical process but is embedded within broader social and institutional contexts.

Customary land governance emerged as one of the most salient socio institutional issues. Much of the ESSC falls under customary land administration, which requires developers and state agencies to engage traditional leaders before projects proceed. Respondents argue that meaningful, timely consultation with traditional authorities and local community is essential for securing social legitimacy, facilitating land access and preventing conflict during project rollout.

Institutional coordination, regulatory uncertainty, and stakeholder participation and community acceptance were cited as the sources of investor unease. First, fragmented responsibilities among municipalities, Eskom, national departments, regulators and private developers generate overlapping mandates, delayed approvals and weak implementation. Second, ambiguity surrounding embedded generation rules, licensing requirements and approval processes, compounded by inconsistent policy priorities, discourages investment despite the region's substantial RE potential. Lastly, sustained stakeholder and community participation is essential for long term project sustainability, as inclusive engagement builds trust, responds to local concerns and strengthens community ownership of RE initiatives.

Finally, institutional capacity was identified as a limiting factor. Shortages of skilled personnel, constrained project management capacity and limited expertise were seen as significant obstacles to planning, construction and maintaining renewable infrastructure in the ESSC. Participants recommended strengthening technical skills, expanding institutional capability and promoting collaboration between government, academia and industry to improve the region's readiness for renewable deployment.

◇ **Scenario Analysis**

The scenario analysis adopts key clean energy production assumptions and data from locally relevant South African studies to ensure contextual accuracy and applicability. Specifically, the wind energy projections draw upon the life cycle external cost assessment of an onshore wind farm by Ibrahim and Thopil (2025), while the solar energy estimates reference the 54 MW solar PV plant by Barnard et al., 2021).

Both studies provide empirically grounded insights that reflect South Africa's unique climatic, economic, and regulatory conditions, strengthening the robustness of this analysis. The capacities considered in this study include a 138 MW wind farm and a 54 MW solar PV plant, sizes that are both practical and scalable within the ESSC region. Primary data obtained from energy sector experts further validates the choice of wind and solar technologies, highlighting their maturity, bankability, and proven abundance based on comprehensive resource mapping and industry experience within South Africa.

Projections for small hydro power were not included in the scenario analysis, as this technology primarily targets communities without access to the main electricity grid, rather than grid-connected areas considered in this study. According to Eskom (2023), Eskom's microgrids provide affordable, renewable electricity to remote communities that are disconnected due to difficult terrain or cannot afford traditional grid connections.

◇ **Status Quo – continued reliance on Eskom electricity**

In the absence of RE alternatives, small businesses in the RNLM and KSDLM municipalities spend, on average, R1,788.89 and R1,402.78 per month on Eskom-supplied electricity, respectively. Annually, this equates to **R21,466.68** for RNLM and **R16,833.33** for KSDLM per business. Although these figures reflect the prevailing operational environment, this situation is economically unsustainable due to escalating tariffs, unreliable electricity supply, and the adverse effects of load shedding. Consequently, these costs should be regarded as a baseline for comparative analysis rather than as a viable long-term solution.

◇ **Scenario 2: Integration of a 138 MW wind farm in the region**

Participants and experts in the study recommended that wind energy can be integrated into

the ESSC area, citing the availability of abundant wind resources confirmed through extensive regional mapping (CSIR,2019) and experience. Wind technology is considered mature and bankable by financial institutions active in South Africa, making such an investment feasible.

Annual electricity generation

For the wind scenario, annual electricity generation was estimated using installed capacity of 138 MW and an assumed capacity factor of 35%. Therefore:

Annual electricity generation

$$\begin{aligned} &= \text{Capacity of a plant (MW)} \times \text{CF} \times \text{number of hours in a year (8 760)} \\ &= 138\text{MW} \times 0.35 \times 8\,760\text{h/year} \\ &= 423\,108\text{ MWh/year} \sim 423\,108\,000\text{ kWh/year} \end{aligned}$$

Displaced Eskom Electricity The displacement Eskom electricity equal to the annual renewable electricity generation as calculated above. Therefore:

$$\begin{aligned} \text{Displaced Eskom electricity} &= \text{Renewable energy generated/year} \\ &= 423\,108\text{ MWh/year} \sim 423\,108\,000\text{ kWh/year} \end{aligned}$$

Avoided Emissions

$$\begin{aligned} \text{Avoided emission} &= \text{Annual renewable electricity generation} \left(\frac{\text{MWh}}{\text{y}} \right) \times \text{grid factor} \\ \text{Avoided emissions} &= 423\,108 \frac{\text{MWh}}{\text{year}} \times (0.942\text{ tCO}_2\text{e}) \\ &= 398,568\text{ tCO}_2\text{e/year} \end{aligned}$$

Indicative gross value of displaced electricity

$$\begin{aligned} \text{Indicative gross value of displaced electricity} &= \\ &\quad \text{Displaced Eskom electricity} \times \text{municipal tariff rate (R/kWh)} \\ &= 423\,108\,000\text{ kWh} \times \text{R}2.45/\text{kWh} \\ &= \text{R }1.04\text{bn/year} \end{aligned}$$

◇ Scenario 3: Integration of a solar plant in the region

Annual electricity generation For the solar scenario, annual electricity generation was estimated using installed capacity of 54 MW and an assumed capacity factor of 26%. Therefore:

Annual electricity generation =

$$\begin{aligned} & \text{Capacity of a plant (MW)} \times \text{CF} \times \text{number of hours in a year (8 760)} \\ &= 54 \text{ MW} \times 0.26 \times 8\,760 \text{ h/year} \\ &= 122,990 \text{ MWh/year} \sim 122\,990\,000 \text{ kWh/year} \end{aligned}$$

Displaced Eskom Electricity

$$\begin{aligned} \text{Displaced Eskom electricity} &= \text{Renewable energy generated/year} \\ &= 122,990 \text{ MWh/year} \sim 122\,990\,000 \text{ kWh/year} \end{aligned}$$

Avoided Emissions

Avoided emissions

$$\begin{aligned} &= \text{Annual renewable electricity generation} \left(\frac{\text{MWh}}{\text{Y}} \right) \times \text{grid factor} \\ &= 122\,990 \frac{\text{MWh}}{\text{year}} \times (0.942 \text{ tCO}_2\text{e}) \\ &= 115,857 \text{ tCO}_2\text{e/year} \end{aligned}$$

Indicative gross value of displaced electricity

Indicative gross value of displaced electricity–

$$\begin{aligned} & \text{Displaced Eskom electricity} \times \text{municipal tariff rate} \\ &= 122\,990\,000 \text{ kWh/year} \times \text{R}2.45/\text{kWh} \\ &= \text{R}301\text{m} \end{aligned}$$

◇ Scenario 4: Integration of wind and solar in the region

Combining the 138 MW wind farm with the 54 MW solar PV plant presents a hybrid RE system that capitalises on resource diversity. Wind energy typically peaks during night-time and in different seasons than solar energy, which is available primarily during daylight hours. This complementary generation profile provides improved energy supply reliability and reduces intermittency challenges inherent to single-source renewables. Furthermore, integrating Battery Energy Storage Systems (BESS) enhances this hybrid set-up by storing excess generation and ensuring steady supply during periods of low wind or solar availability. This integrated approach promotes grid resilience, supports load balancing, and reduces reliance on Eskom's increasingly expensive and unreliable electricity supply.

◇ **Optimal solution**

Hybrid annual generation Assuming both facilities operate simultaneously, total annual electricity generation would be:

$$\begin{aligned}
 \text{Total electricity generation} &= \text{Wind annual electricity generation} \\
 &+ \text{solar annual electricity generation} \\
 &= 423\,108 \text{ MWh/year} + 122\,990 \text{ MWh/year} \\
 &= \mathbf{546,098 \text{ MWh/year} \sim 546\,098\,000 \text{ kWh}}
 \end{aligned}$$

Total displaced Eskom electricity = **546,098 MWh/year $\sim$ 546 098 000 kWh**

$$\begin{aligned}
 \text{Total Avoided emissions} &= 398,568 \text{ tCO}_2\text{e/year} + 115,857 \text{ tCO}_2\text{e/year} \\
 &= \mathbf{514,425 \text{ tCO}_2\text{e/year}}
 \end{aligned}$$

$$\begin{aligned}
 \text{Total indicative gross value of displaced electricity} &= \text{R1.04bn} + \text{solar R301m} \\
 &= \mathbf{\text{R1.34bn}}
 \end{aligned}$$

The hybrid RE scenario combines wind and solar photovoltaic generation to improve electricity reliability and reduce variability associated with individual RE technologies. Wind resources along the Eastern Seaboard region are generally stronger during evening and winter periods, while solar photovoltaic generation reaches its peak day light hours. Combining these generation profiles with battery energy storage improves system flexibility, enhances electricity reliability and reduces dependence on conventional grid electricity.

Consequently, the hybrid scenario represents the preferred pathway for RE integration within the proposed ESSC. By diversifying the energy portfolio, the region can reduce exposure to tariff escalations and load shedding, aligning with South Africa's national decarbonisation goals and improving local economic resilience. Summary of RE scenario and projected outcomes for the projected ESSC is shown in Table 5 below.

Table 5: Summary of RE scenario analysis and projected outcomes for the proposed ESSC

Scenario	Installed capacity (MW)	Annual generation (MWh/year)	Displaced Eskom electricity (MWh/year)	Avoided emissions (tCO ₂ e/year)	Indicative gross value of displaced electricity (R/year)
Status quo	Existing grid	Baseline	Baseline	Baseline	Baseline
Wind	138 MW	423,108	423,108	398,568	1.04bn
Solar	54 MW	122,990	122,990	115,857	301m
Wind + solar	192 MW	546,098	546,098	514,425	1.34bn

Source: Author's own computation from published secondary parameters, Ibrahim and Thopil (2025), Barnard et al. (2021), CSIR (2025), DFFE (2025) and the RNLM tariff schedule, (2025)

The RE scenarios were evaluated at the original scale of the proposed ESSC. Electricity expenditure data sampled small businesses were used solely to establish a descriptive baseline of local electricity affordability and were not intended to represent the total electricity demand of the proposed smart city. Therefore, scenarios should be interpreted as comparative planning estimate rather than project specific technical and financial forecast.

The findings of the study indicate that RE integration within ESSC is influenced by five interrelated dimensions. First, the region possesses favourable RE resources, particularly wind and solar photovoltaic potential. Second, inadequate transmission infrastructure and grid capacity constraints on integration of new renewable generation. Third, financing requirements and investor confidence remain significant implementation barriers. Fourth, institutional coordination between municipalities, national government, Eskom and regulators is essential for successful implementation. Finally, traditional land governance emerged as a distinctive contextual factor shaping infrastructure development within the ESSC, highlighting that RE deployment depends not only on technical feasibility but also on culturally appropriate governance arrangements.

5 Discussion

The findings demonstrate that RE integration within the ESSC extends beyond the technical suitability for RE. Although participants consistently identified wind and solar technologies as the most feasible RE options due to the region's favourable climatic conditions and the maturity of these technologies, the study indicates that technical resource alone is insufficient to guarantee successful implementation. Current studies have extensively documented the economic competitiveness and technical viability of wind and solar in South Africa. The study supports these findings but extends them by demonstrating that RE deployment within ESSC is equally dependent on institutional coordination, electricity infrastructure, financing mechanisms and governance arrangements. Consequently, RE planning should be understood as a socio technical process rather than a technical and financial issue.

Institutional theory: Explaining governance barriers

Institutional Theory offers a valuable framework for interpreting the governance challenges identified in this study. The theory posits that organisations operate within institutional environments shaped by formal regulations, informal norms and socially embedded practices. Consequently, RE implementation in the ESSC is influenced not only by technical and engineering requirements but also by the institutional arrangements that govern planning, and regulation execution.

Participants consistently pointed to fragmented responsibilities among municipalities, Eskom, the NERSA, national government departments and IPPs as a key barrier to RE deployment. These silos undermine institutional coordination, slow decision making and constrain infrastructure investment, despite the region's substantial RE potential. In addition, participants also emphasised the need to engage traditional leadership structures when proposed RE infrastructure is located on customary land. This indicates that institutional legitimacy extends beyond statutory government processes to include customary governance systems that shape land access, community acceptance and project outcomes. In this regard,

Institutional Theory assists in explaining why technically feasible RE projects may still face implementation delays when institutional arrangements are fragmented or lack legitimacy.

Multi-Level Perspective (MLP): Energy transition

In the essence of this study, MLP clarifies how South Africa's electricity system is characterised by gradual change. Under MLP the established centralised system dominated by Eskom constitutes the incumbent socio technical regime while wind and solar technologies occupy niche positions as emerging innovations. Landscape pressures such as the persistent supply crisis, ageing infrastructure, rising tariffs and national decarbonisation commitments are weakening the incumbent and creating space for these niche technologies to expand. Participants' preferences for hybrid renewable systems supported by BESS signals a pragmatic emergent pathway in which decentralised generation mitigates supply risk and complements existing infrastructure rather than displacing it.

Therefore, the study findings point to a staged transition rather than sudden substitution. In this model the ESSC could operate as a regional demonstration site where niche renewables incrementally integrate with the dominant regime, showcasing technical feasibility, building institutional capacity and strengthening community acceptance. Such approach would both enhance energy security and catalyse local economic development, illustrating how niche innovations can scale through incremental alignment with policy, markets and existing grid arrangements.

Traditional land governance

The principal contribution of the study is to illuminate the role of traditional land governance in shaping RE deployment within the ESSC. While prior research has largely emphasised resource endowments, grid capacity, financial viability and regulatory conditions, participants in this study repeatedly identified customary land governance as a determining factor for project feasibility. Much of the proposed development corridor lies on the land administered by traditional authorities, and participants stressed that meaningful engagement with traditional leaders, community representatives, and customary governance institutions is required throughout project planning, land acquisition and implementation. Failure to recognise these governance arrangements can generate conflict, erode community acceptance and delay project delivery, irrespective of the technical soundness of proposed infrastructure.

These findings advance the existing RE literature by demonstrating that institutional legitimacy in rural and peri urban settings is co-produced through statutory government mechanisms and customary governance systems. Accordingly, RE implementation must be conceived as both a technical and a socio institutional endeavour that demands culturally appropriate, sustained stakeholder engagement. For policy makers and project developers this entails moving beyond conventional permitting processes to adopt participatory approaches that acknowledge customary land rights, build local trust and align project benefits with community priorities.

The potential for renewable energy sources and their integration into the city's electricity solution

The study affirms the RE potential in the ESSC, particularly for wind and solar, highlighting their technical advantages and broad stakeholder support. This is strongly aligned with studies by Mutombo and Numbi (2019) and the IPP Office (2021); these studies underscore the substantial wind capacity in the Eastern Cape and significant solar radiation across KwaZulu-Natal. A notable similarity is the cross-verification of local resource mapping with established literature, which grounds policy recommendations in empirical resource assessments. Where they differ is in the explicit focus on site-specific challenges in the ESSC, such as logistical difficulty and environmental constraints associated with small hydroelectric projects. This difference arises due to the present study's context-sensitive approach, which is less prominent in the more macroscopic literature reviewed.

Stakeholder consultations highlighted several technical and logistical barriers to RE integration. Key constraints include inadequate infrastructure, limited energy storage capacity, and weak grid integration mechanisms, especially in rural and peri-urban areas of the ESSC. Experts from academia and the private sector emphasised the necessity for technology solutions tailored to local conditions, considering terrain, population density, and resource reliability. The adoption of decentralised energy systems and microgrids was strongly advocated as a strategic approach to avoid grid limitations, enhance energy security, and promote localised control. Furthermore, the study underscores the critical need for comprehensive planning and investment in advanced technologies and infrastructure to realise the full benefits of RE.

Strengthening policy and regulatory frameworks emerged as equally important, with participants noting that while national policies such as the Integrated Resource Plan (IRP, 2025) provide a foundational framework, local implementation is often undermined by weak enforcement and governance challenges. A coordinated, multi-stakeholder approach supported by clear regulatory incentives is essential to unlocking the ESSC's RE potential, thereby improving electricity reliability and advancing environmental sustainability through reduced greenhouse gas emissions.

The research highlights that while national policy frameworks like the IRP 2025 provide direction, implementation locally is undermined by regulatory weaknesses and governance gaps. This is similarly voiced in the literature, where Yelland (2020) as well as Khonjelayo and Nthakheni (2020) diagnosed weak enforcement, outdated regulations, and a lack of political will as primary blockages. The similarity is clear: South Africa's sound policy intentions are regularly frustrated by execution bottlenecks at provincial or municipal levels.

Where the findings differ from established research is the identification of traditional governance and rural socio-political systems as key local barriers, a nuance less developed in national-level critiques. The reasons for this difference stem from the embeddedness of the current research in specific, rural community experiences.

The economic, social, and environmental benefits of implementing a smart electricity solution in the city

The anticipated environmental benefits of integrating RE into the ESSC are significant. Most participants, identified a reduced carbon footprint as the foremost advantage, reflecting ex-

expectations that renewables will displace fossil fuel use and lower greenhouse gas emissions, thereby improving air quality. On the other hand, only a small minority of the participants highlighted biodiversity preservation, recognising that wind, solar, and small hydro systems cause less ecological disturbance than coal or large hydro projects. This environmental stewardship is crucial for protecting the ESSC's terrestrial and coastal ecosystems, which underpin the region's natural heritage and eco-tourism potential.

Both the ESSC stakeholder responses and the reviewed literature widely agree that RE introduction, especially wind and solar, leads to a marked reduction in carbon emissions and fossil fuel dependence, as well as improved air quality and biodiversity preservation. Kumba et al. (2024) and CSIR (2023) report on such benefits, identifying reduced environmental footprint as a primary driver for RE advocacy. The commonality is strong alignment in recognising the environmental upside of RE. Differences are negligible, except for the study's more detailed enumeration of supplementary ecological benefits (e.g., minimal disruption compared to coal or large hydro). This greater specificity is due to the mixed-methods engagement with local stakeholders, which adds qualitative depth.

From an economic perspective, participants emphasised job creation, and the expansion of business operations as primary benefits of RE integration. Affordable local electricity supply was noted by recognising access to international markets and carbon credit opportunities. Furthermore, carbon credits and green branding offer new revenue streams that can be reinvested to bolster economic resilience and development. Participants in the ESSC indicate job creation, SMME expansion, and affordable local electricity as major benefits, corroborating the claims by Kumba et al. (2024), who documented the green jobs and economic multipliers associated with RE.

The scenario analysis demonstrates that a hybrid system combining wind, solar, and battery storage can effectively address grid instability and reduce reliance on Eskom, supporting findings from Mashau and Kroeze (2023) regarding the limitations of existing infrastructure and the need for diversified energy sources. The hybrid scenario offered the greatest potential to reduce greenhouse gas emissions by displacing grid generation that remains largely fossil fuelled. Therefore, these results indicate that a diversified renewable portfolio presents a pragmatic route to strengthen energy security, support regional economic development and accelerate South Africa's decarbonisation goals in the ESSC.

6 Conclusions and recommendations

6.1 Conclusions

This study concludes that the ESSC region has substantial potential for RE integration, particularly through wind and solar PV technologies. The scenario analysis shows that a 138 MW wind configuration could potentially generate approximately 423 108 MWh of electricity annually, while a 54 MW solar PV configuration could potentially generate approximately 122 990 MWh annually. A hybrid wind-solar configuration could generate approximately 546 098 MWh per year, which is the greatest potential for renewable electricity generation among the scenarios assessed.

Using the adopted South African emission factor, the wind, solar PV and hybrid configurations could avoid approximately 398 568 tCO₂e, 115 857 tCO₂e and 514 425 tCO₂e annually, respectively. The hybrid configuration consequently offers the potential to reduce reliance on grid supplied electricity and displace grid related emissions. The findings further show that wind and solar resource availability alone is insufficient to enable successful RE integration. Inadequate electricity infrastructure, limited grid capacity, financing constraints, institutional fragmentation and regulatory uncertainty remain key barriers to RE deployment.

Moreover, the study highlights the importance of customary land governance in determining the feasibility and legitimacy of RE infrastructure in the ESSC region. RE projects on land governed through customary structures require sustained and meaningful engagement with traditional authorities and affected communities. This engagement is necessary to secure land access, strengthen community acceptance and reduce implementation risks. RE deployment in rural and peri urban areas should therefore be understood as a technical, institutional and socio-cultural process.

The study concludes that the ESSC requires a coordinated and phased RE strategy that integrates wind and solar PV generation with reinforcement and energy storage. Its implementation will require effective coordination among municipalities, Eskom, national government departments, regulators, independent power producers, traditional authorities and local communities. The scenario results should be interpreted as indicative planning estimates rather than project specific financial forecasts, as the analysis excludes capital expenditure, financing costs, operation and maintenance costs, storage dispatch, curtailment and other project specific system costs.

6.2 Recommendations

The study recommends that the ESSC adopt a phased hybrid RE system combining wind, solar and a battery storage, supported by upgrades to grid infrastructure, substations and transmission networks. Municipalities, Eskom, NERSA, government departments, IPPs, traditional authorities and local communities should establish coordinated planning and implementation mechanisms to reduce regulatory uncertainty, strengthen institutional capacity and accelerate project approvals.

RE projects in the ESSC should be guided by detailed resource assessment, grid impact studies and techno economic feasibility studies, while meaningful consultation with traditional authorities and affected communities should inform land access, benefit sharing, local procurement and employment opportunities. Municipalities should also invest in technical skills, local SMME participation and ongoing monitoring of electricity reliability, affordability, emissions reduction and socio-economic benefits to ensure the RE integration supports an inclusive, resilient and low carbon smart city.

Disclosures statements

The authors declare that there is no conflict of interest associated with this research.

Funding

The Master's report from which this paper was extracted was funded by the South African Energy and Water Sector Education and Training Authority (EWSETA).

Data availability

Data will be made available upon reasonable request

References

1. Barnard, S. S. S., Smit, A. M., Middelberg, S. L., & Botha, M. J. (2021). A cost-benefit analysis of implementing a 54 MW solar PV plant for a South African platinum mining company: A case study. *Journal of Energy in Southern Africa*, 32(3), 76–88. Available: <https://doi.org/10.17159/2413-3051/2021/v32i3a11604>
2. Butt, O. M., Zulqarnain, M., & Butt, T. M. (2021). Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal*, 12(1), 687–695. Available: <https://doi.org/10.1016/j.asej.2020.05.004>
3. Case Western University. (2024). Building smart cities and infrastructure. Available: <https://online-engineering.case.edu/blog/building-smart-cities-and-infrastructure>
4. Council for Scientific and Industrial Research. (2019). Additional renewable energy development zones proposed for wind and solar PV. Available: <https://www.csir.co.za/renewable-energy-development-zones>
5. Council for Scientific and Industrial Research. (2023). Just Energy Transition: CSIR and key energy stakeholders launch Microgrid Centre of Excellence. Available: <https://www.csir.co.za/csir-and-key-energy-stakeholders-launch-microgrid-centre-excellence>
6. Council for Scientific and Industrial Research. (2025). Utility-scale power generation statistics in South Africa 2024 (1 January 2024–31 December 2024) [Report]. Available: https://www.csir.co.za/sites/default/files/202509/Utility%20Statistics%20Report_Jan%202025_Final.pdf
7. Department of Cooperative Governance and Traditional Affairs. (2025). Eastern Seaboard Development. Available: <https://www.cogta.gov.za/index.php/eastern-seaboard-development/>
8. Department of Electricity and Energy. (2025). Integrated Resource Plan 2025. Available: <https://www.dmpr.gov.za/Portals/0/Energy%20Resources/IRP/IRP%202025/Integrated-Resource-Plan-2025.pdf?ver=o8tx64Is6UjUdY0b4F6kVg%3d%3d>
9. Department of Forestry, Fisheries and the Environment. (2025). South Africa's 2023 grid emission factors report (Government Notice No. 6454, Government Gazette No 53079). Available: https://www.gov.za/sites/default/files/gcis_document/202507/53079gon6454_0.pdf
10. Department of Mineral Resources and Energy. (2024). The South African energy sector report 2024. Available: <https://www.dmre.gov.za/Portals/0/Energy%20Resources/Energy%20Sector%20Reports/2024-South-African-EnergySectorReport.pdf?ver=iMEAU9eNGIImZAImSJyhjA%3D%3D>
11. Development Bank of Southern Africa. (2024). How DBSA powers rural communities through tech infrastructure development. Available: <https://www.dbsa.org/artic>

le/how-dbsa-powers-rural-communities-through-tech-infrastructure-development

12. DiMaggio, P. J., & Powell, W. W. (1983). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review*, 48(2), 147–160. Available: <https://research.ebsco.com/c/zmu5bf/viewer/pdf/vwtseacri5>
13. Du Toit, B. R., & Stimie, J. E. (2023). Towards smart cities in South Africa: evolution, definitions, and future cities. *South African Journal of Industrial Engineering*, 34(1), 85–96. Available: <http://dx.doi.org/10.7166/34-1-2839>
14. Eastern Cape Department of Economic Development, Environmental Affairs and Tourism. (2012). Eastern Cape Renewable Energy Strategy Executive Summary. Available: https://www.cityenergy.org.za/uploads/resource_183.pdf
15. Eskom Holdings SOC Limited. (2020). Integrated report. Available: https://www.eskom.co.za/wpcontent/uploads/2021/06/2020IntegratedReport_secured.pdf
16. Eskom Holdings SOC Limited. (2023). Eskom rolls out microgrid as part of efforts in achieving universal access to electricity using clean and reliable technologies. Available: <https://www.eskom.co.za/eskom-rolls-out-microgrid-as-part-of-efforts-in-achieving-universal-access-to-electricity-using-clean-and-reliable-technologies/>
17. Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, 31(8–9), 1257–1274. Available: [https://doi.org/10.1016/S0048-7333\(02\)00062-8](https://doi.org/10.1016/S0048-7333(02)00062-8)
18. Ibrahim, H. A., & Thopil, G. A. (2025). Life cycle external cost assessment of an on-shore wind farm in South Africa. *Applied Energy*, 388, 125708. Available: <https://doi.org/10.1016/j.apenergy.2025.125708>
19. Independent Power Producer Office. (2021). December 2021 REIPPPP focus on Eastern Cape. Provincial report. Available: <https://www.ipp-projects.co.za/mediaarchives/>
20. International Trade Administration. (2024). South Africa country commercial guide: Energy. Available: <https://www.trade.gov/country-commercial-guides/south-africaenergy#:~:text=Eskom%2C%20the%20vertically%20integrated%2C%20state,secure%20supplies%20for%20South%20Africa.>
21. Khonjelwayo, B., & Nthakheni, T. (2020). Investment in electricity distribution capital infrastructure in South Africa: The role of regulation. *South African Journal of Economic and Management Sciences*, 23(1), 1–10. Available: <http://dx.doi.org/10.4102/sajems.v23i1.3413>
22. Kumba, H., Olanrewaju, O. A., & Pasipamire, R. (2024). Integration of Renewable Energy Technologies for Sustainable Development in South Africa: A Focus on Grid-Connected PV Systems. *Energies*, 17(12), 2823. Available: <https://doi.org/10.3390/en17122823>

23. Maluleke, R. (2022). Mid-year population estimates, 2022. Department of Statistics South Africa. Available: <https://www.statssa.gov.za/publications/P0302/MidYear2022.pdf>
24. Mashau, N. L., & Kroeze, J. H. (2023). Challenges that affect smart city implementation in small and rural municipalities. *South African Journal of Information Management*, 25, 1703. Available: https://hdl.handle.net/10520/ejc-info_v25_n1_a1703
25. Mchunu, N. M., Onatu, G. O., & Gumbo, T. (2023). The impact of electricity blackouts and poor infrastructure on the livelihood of residents and the local economy of City of Johannesburg, South Africa. *arXiv preprint arXiv:2311.08929*. Available: <https://doi.org/10.48550/arXiv.2311.08929>
26. Moulla, D. K., Attipoe, D., Mnkandla, E., & Abran, A. (2024). Predictive model of energy consumption using machine learning: a case study of residential buildings in South Africa. *Sustainability*, 16(11), 4365. Available: <https://doi.org/10.3390/su16114365>
27. Municipal Infrastructure Support Agent. (2023). Draft Eastern Seaboard Regional Spatial Development Framework 2023: Spatial proposals and implementation framework. Available: <https://www.misa.gov.za/wp-content/uploads/2023/02/DRAFT-EASTERN-SEABOARD-RSDF-2023.pdf>
28. Mutombo, N. M. A., & Numbi, B. P. (2019). Assessment of renewable energy potential in Kwazulu-Natal province, South Africa. *Energy Reports*, 5, 874–881. Available: <https://doi.org/10.1016/j.egyr.2019.07.003>
29. Ndubuisi, G., Avenyo, E. K., & Asiam, R. (2025). Dancing on the grid: Electricity crises, energy vulnerability, and manufacturing jobs in South Africa. *Energy Policy*, 202, 114534. Available: <https://doi.org/10.1016/j.enpol.2025.114534>
30. Oke, A. E., Aghimien, D. O., Aigbavboa, C. O., & Akinradewo, O. I. (2020). Appraisal of the drivers of smart city development in South Africa. *Construction Economics and Building*, 20(2), 109–126. Available: <https://search.informit.org/doi/10.3316/informit.342138636869520>
31. Ray Nkonyeni Local Municipality. (2025). Electricity tariffs: Effective 1 July 2025. Draft Available: <https://rnm.gov.za/images/docs/BudgetsReports/2025/thobile/Annexure%201.2%20Draft%20Electricity%20Tariffs%202025-26.pdf>
32. Statistics South Africa. (2023). Poverty trends in South Africa: An examination of absolute poverty between 2006 and 2023 (Report No. 03-10-06). Available: <https://www.statssa.gov.za/publications/Report-03-10-06/Report-03-10-062023.pdf>
33. Tazvinga, H., Dzobo, O., & Mapako, M. (2020). Towards sustainable energy system options for improving energy access in Southern Africa. *Journal of Energy in Southern Africa*, 31(2), 59–72. Available: <https://doi.org/10.17159/2413-3051/2020/v31i2a6504>

34. Yelland, C. (2020). South Africa's Energy Policies. Are Changes Finally Coming?. Available: <https://inis.iaea.org/records/7nxwj-93638>
35. Zondi, S. P., & Qwabe, B. R. (2022). Infrastructure-led Development and Quality Education: Implications for uMzumbe Local Municipality in KwaZulu-Natal. *African Journal of Governance and Development*, 11(1.1), 190–212. Available: https://journals.co.za/doi/epdf/10.10520/ejc-ajgd_v11_n1.1_a10