Challenges and Solutions for Renewable Electricity Integration in South Africa's Power System

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Note: This is NOT a thesis (PhD only) and NOT a dissertation

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ABSTRACT

This study explored the challenges and solutions for integrating renewable electricity into South Africa’s power system focusing on balancing decarbonisation objectives with grid reliability while ensuring equitable access. Employing a qualitative research approach with semi-structured interviews of 11 energy sector stakeholders, the study examined three key research questions: an effective combination of utility-scale renewable technologies; the integration of decentralised systems with grid modernisation and policy frameworks needed for a just transition in coal-dependent communities. The findings revealed that successful renewable integration requires strategic geographic deployment of complementary technologies with solar resources concentrated in the Northern Cape and wind potential along coastal regions. Significant infrastructure constraints necessitate substantial transmission development to connect resource-rich areas with demand centres. For rural and peri-urban regions, decentralised systems prove effective when implemented with community participation while grid modernisation must be carefully sequenced to prevent system instability. In coal-dependent communities, particularly Mpumalanga, effective transition requires multidimensional approaches addressing economic security, skills development and community ownership. The study contributes to knowledge by identifying implementation gaps between theoretical resource potential and practical deployment, emphasising the importance of governance models in decentralised systems and highlighting the critical sequencing of just transition interventions. Recommendations include region-specific renewable deployment, streamlined regulatory processes, community engagement frameworks and carefully sequenced economic support for coal- dependent regions. These findings provide valuable insights for policymakers, industry practitioners and communities navigating South Africa's complex energy transition landscape.

KEY WORDS

Energy security, Energy access, Energy, Sustainable energy supply

DECLARATION

I, __Nthabiseng K. M. Mabuza___________, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in Energy Leadership at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Name: Nthabiseng K. M. Mabuza Signature:

Signed at ……Ekurhuleni………………………………………………

On the …………13…………………. day of ………September……… 2024….

DEDICATION

I dedicate this research report to my family, whose unwavering support, encouragement and understanding has been instrumental in this journey. Their guidance, patience, and belief in my abilities have motivated me to persevere and achieve my goals.

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I would like to express my deepest gratitude to everyone who contributed to the successful completion of this research report.

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LIST OF ACRONYMS AND ABBREVIATIONS

ESKOM - Electricity Supply Kommission

MW - Megawatts

SA – South Africa

JT – Just Transition

CO_2 – Carbon dioxide

PV - Photovoltaic

DMRE - Department of Mineral Resources and Energy

IRP - Integrated Resource Plan

1. INTRODUCTION

1.1. Purpose of the study

The study explores the role of renewable electricity integration in ensuring system reliability while supporting South Africa's (SA) transition to a lower-carbon electricity grid.

1.2. Context of the study

1.2.1 Sectoral Distinction and Historical Evolution

It is essential to distinguish electricity from SA's broader energy sector. Although public discourse frequently conflates these concepts, SA's energy sector heavily relies on coal, which constitutes 67% of total primary energy sources (Ayodele & Munda, 2019). Therefore, SA's energy mix includes electricity, liquid fuels and direct coal use, with the industrial and residential sectors being the primary consumers (Ayodele & Munda, 2019). Hence, this distinction is fundamental for comprehending the specific challenges confronting the electricity sector.

South Africa's electricity sector, historically dominated by Eskom (a vertically integrated public utility that is a predominant player in the sector), is undergoing significant restructuring to foster competition and improve performance (Hansen, 2000; Buraimoh et. al, 2020). This sector grapples with aligning complex sustainability objectives within electricity planning, necessitating a rethink of current practices (Brent, Mqadi & Musango, 2018). Despite efforts towards reform, significant political, economic, technical and regulatory challenges persist in achieving a just and inclusive energy transition (Baker & Phillips, 2019).

The institutional framework of the electricity sector was established through several significant legislative developments, such as the Power Act of 1910. Leading to the government intervention in privately owned electricity enterprises, that further advanced by the transformative Electricity Act of 1922. With this legislation, the ESKOM was established in 1923, centralising electricity planning and development (Hendrickse, 2022). The current regulatory landscape is shaped by:

Institution	**Purpose**	**Key Linkages**
National Energy Act (2008)	Provides overarching energy policy framework, promotes diverse energy resources, energy efficiency, and security at affordable prices, supporting economic growth and poverty alleviation.	Guides IRP, REIPPPP, and NERSA's regulatory functions.
Electricity Regulation Amendment Act (2024)	Reforms electricity market, introduces competition, establishes Transmission System Operator and Enables private sector participation in electricity generation	Amends Electricity Regulation Act (2006), impacts NERSA, Eskom unbundling, and private sector participation.
Integrated Resource Plan IRP 2023/2024	20-year electricity generation roadmap	Guides REIPPPP, NERSA licensing, and Eskom's generation plans.
Energy Action Plan (2022)	Emergency measures to end load-shedding (fast-tracking renewables IPP's, fixing Eskom and boost renewables)	Works with REIPPPP, IRP, and NERSA licensing.
Municipal Systems Act (2000)	Governs municipal service delivery, including electricity distribution.	Affects municipal electricity distributors, NERSA tariff approvals, and Eskom's distribution arm.
National Energy Regulator of South Africa (NERSA)	Independent regulator for electricity, gas, and petroleum pipelines.	Implements ERA Bill, approves tariffs, licensing IPPs, oversees Eskom & municipal compliance.

Table 1 Legislative & Policy Framework Overview

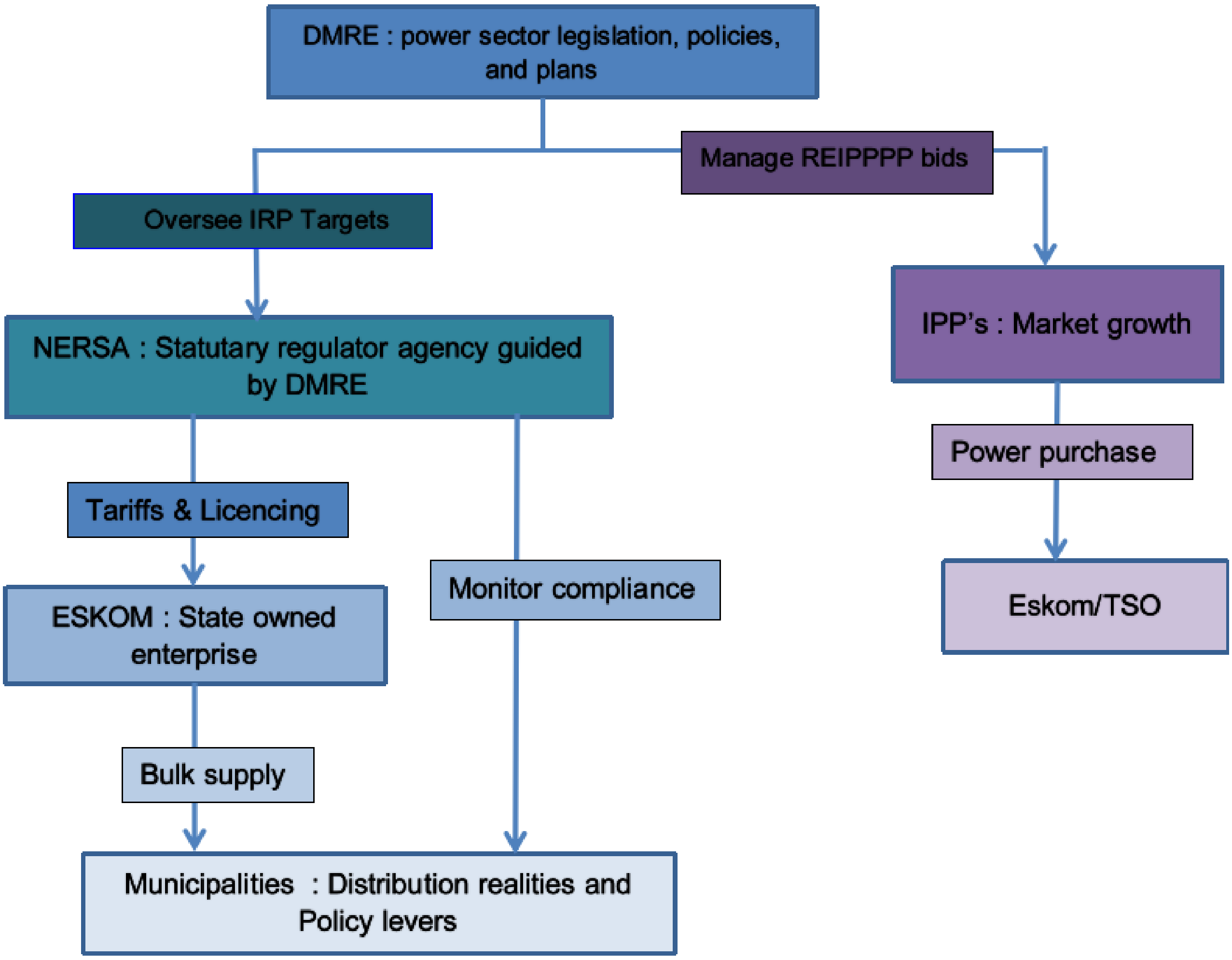

Figure 1 Policy actor Map Source: The South African Power Sector.

1.2.2 Economic Context and De-industrialisation

South Africa has undergone substantial de-industrialisation since it transitioned to democracy (Slater, 2001; Andreoni & Tregenna, 2018) has altered electricity demand patterns, complicating system planning. Moreover, SA has prematurely de-industrialised (Bell et al.,2018). Key drivers include declining heavy industry (e.g., steel, smelting) due to unreliable power and high costs and uncertain electricity future demand due to factors such as climate change, e-mobility and electric heating/cooling (Kan, Reichenberg & Hedenus, 2021). As a result, de-industrialisation has coincided with alterations in electricity consumption patterns, presenting new challenges for system planning and reliability.

1.2.3 Contemporary System Dynamics

The current electricity landscape presents a complex set of challenges and contested solutions. While access rates have improved significantly to over 90% in 2022 (Toto, 2022), the system faces severe constraints such as frequent power outages and load shedding exacerbated by aging infrastructure and insufficient generation capacity regularly disrupt economic activity and burden households (Skosana, Siti, Mbungu, Kumar & Mulumba, 2023**)**.

1.2.4 Critical Debates in Renewable Integration

The role of renewable electricity in SA's future has emerged as a subject of intense scholarly and policy debate. Rather than accepting renewables as an uncontested solution, the discourse reveals complex technical, economic and systemic challenges that require thorough consideration. The technical feasibility of large-scale renewable integration remains a particularly contentious issue. Baker and Phillips (2019) raise significant concerns regarding grid stability under high renewable penetration scenarios. Their research highlights how inverter-based generation fundamentally alters system dynamics, potentially compromising grid stability due to a diminished inertial response. Moreover, they emphasise challenges in voltage control and frequency regulation noting that system recovery after disturbances becomes increasingly complex as renewable penetration intensifies. In contrast, Gui, et al., (2024) present a more optimistic perspective, arguing that modern grid technologies can effectively address the current challenges faced in controlling transmission grids. This is illustrated by the capabilities of advanced grid monitoring and control systems, energy storage technologies and flexible grid infrastructure (Gui, et al., 2024). Nevertheless, both sides of this debate acknowledge the necessity for substantial investments in grid infrastructure (Goga, 2024).

The economic dimension of renewable electricity integration introduces an additional layer of complexity. The Energy Systems Research Group (2023) has documented that public discourse frequently concentrates narrowly on generation costs, neglecting broader economic implications. Whereas Aunedi, Pudjianto and Strbac, (2016) analysis delineates various cost layers, commencing with direct expenditures related to generation equipment, installation infrastructure and maintenance requirements. Beyond these immediate costs, significant system integration expenses encompass grid reinforcement, backup generation capacity and upgrades to control systems (VanderMeer, Mueller-Stoffels & Whitney, 2017). Furthermore, the analysis extends to societal costs, addressing issues such as land use changes, the impacts of material extraction, waste management considerations and employment transitions within affected communities.

System adequacy emerges as a third critical concern in the renewable integration debate. Doorga, Hall & Eyre, (2022) study presents compelling data about the inherent limitations of renewable generation. Based on their study, the analysis shows that solar photovoltaic (PV) installations in SA typically achieve capacity factors between 20-30% while wind installations reach 35-45% in ideal locations. These limitations are worth noting, combined with weather dependency and geographic concentration of renewable resources and they raise fundamental questions about system reliability and the security of electricity supply. Implementation requirements for renewable integration form a crucial part of this ongoing debate. This highlights that successful integration demands a comprehensive approach to infrastructure development, as argued by Al-Shetwi, Hannan, Jern, Mansur & Mahlia (2020). This understanding is crucial as enhanced transmission networks are included and advanced control systems capable of managing increasingly complex grid operations. The key implication drawn from this is the importance of storage facilities and flexible generation capacity in maintaining system stability (Stenclik, Denholm & Chalamala, 2017). However, there are economic implications associated with maintaining and implementing these requirements as they extend beyond direct infrastructure costs. This calls attention to policy frameworks addressing investment incentives, technical standards and market structures that enable effective integration while maintaining system reliability (Kozlova & Lohrmann, 2021).

These debates surrounding renewable integration reveal the complexity of SA's electricity transition. Therefore, success requires careful consideration of technical constraints, economic implications and system reliability requirements. This highlights that while renewable energy offers significant potential benefits, its integration demands a nuanced approach that acknowledges and addresses multiple technical, economic and social challenges. Moreover, these debates surrounding renewable electricity integration in SA reveal the complexity of transforming an established electricity system. Rather than accepting renewable integration as an uncontested solution, policymakers and technical planners must carefully consider multiple perspectives and challenges to develop effective, sustainable approaches to system transformation.

1.2.5 Synthesis of the Current SA Electricity Supply

South Africa's electricity sector faces multifaceted challenges demanding sophisticated solutions. While renewable technologies present promising opportunities for system transformation, their integration into the existing electricity infrastructure requires careful consideration of technical, economic and social dimensions. Hence, the evidence from current research and industry experience suggests that addressing these challenges requires a comprehensive approach that goes beyond simple technical solutions (Eyre, Darby, Grünewald, McKenna & Ford, 2018).

The need for a balanced technology mix is at the heart of a successful transition. This encompasses the integration of renewable electricity sources and the maintenance and development of dispatchable generation capabilities. As a result, substantial investment in grid infrastructure becomes crucial to enable this technological diversity and ensure system stability. According to Kabeyi and Olanrewaju (2022), this balanced approach provides the foundation for reliable electricity supply while facilitating the transition to more sustainable generation sources. Thus, Neshat, Amin-Naseri & Ganjavi, (2017) proposed a game-theoretic model approach that can help balance supply and demand in transitioning electricity markets, providing competitive conditions for renewable expansion.

SA's electricity challenges demand thoughtfully constructed, comprehensive solutions rather than simplified approaches (Mqadi et al., 2018). Most prior research studies fail to take into account the importance of balancing technical feasibility, economic viability and social equity considerations in electricity planning (Tarekegne, Kerby, Bharati & O'Neil, 2022). For this purpose, success depends on maintaining system reliability while promoting environmental sustainability through well-planned and properly executed initiatives (Karevan & Vasili, 2018). As Xaba, (2023) notes, this transition represents not just a technical challenge but a fundamental transformation of SA's electricity system that must be managed with careful attention to all stakeholders' needs and concerns.

1.3. Research problem

South Africa faces a multifaceted energy crisis characterised by inadequate electricity supply, ageing infrastructure and heavy reliance on coal-based generation (Nhleko & Inambao, 2020; Ghajiga & Warlimont, 2021). The main challange being the existing energy infrastructure that is 77% reliant on fossil fuels plants that are increasingly unsustainable with an energy availability factor of up to 55%(Eskom, 2023) leading to frequent load shedding and environmental concerns (Uhunamure & Shale, 2021). Secondly rural households pay 40% more for unreliable electricity (Sarkodie & Adams, 2020), exacerbates socio-economic inequalities. Addressing these challenges requires a comprehensive approach that balances the immediate need for reliable energy with long-term goals for sustainability and equity.

South Africa currently has limited access to consistent, sustainable and affordable electricity which exacerbates socioeconomic inequalities (Sarkodie & Adams, 2020). In post-apartheid SA's democratic government has committed to retaining electricity distribution and reducing societal inequalities by adopting pro-poor policies. The intention of the government was to address electricity access and affordability, which has produced many benefits for its population but has also led to distributive injustice.

1.4. Research questions

1.4.1. What combination of utility-scale solar PV, wind energy and grid-scale battery storage technologies can most effectively balance SA's decarbonisation objectives with grid reliability, leveraging the country's geographic distribution of solar and wind resources?

1.4.2. How can phased integration of decentralised renewable energy systems (e.g., mini-grids, solar home systems) and modernisation of transmission infrastructure accelerate equitable electricity access and decarbonisation in SA's rural and peri-urban regions? ?

1.4.3. What policy frameworks and localised initiatives (e.g., skills retraining, community-owned renewable projects) are critical to ensuring a just transition for coal-dependent communities such as Mpumalanga while fostering economic diversification through renewable energy sectors?

1.5. Research Objectives

1.5.1. To determine the most suitable combination of utility-scale solar PV, wind energy and grid-scale battery storage technologies that effectively balances South Africa's decarbonisation objectives with grid reliability by leveraging the country's geographic distribution of solar and wind resources.

1.5.2. To evaluate how phased integration of decentralised renewable energy systems (including mini-grids and solar home systems) combined with transmission infrastructure modernisation can accelerate equitable electricity access and decarbonisation in South Africa’s rural and peri-urban regions.

1.5.3. To identify and assess the policy frameworks and localised initiatives (such as skills retraining and community-owned renewable projects) that are critical for ensuring a just transition for coal-dependent communities like Mpumalanga while fostering economic diversification through renewable energy sectors.

1.6. Significance of the study

SA faces significant challenges in providing sustainable and reliable electricity to its population, directly impacting economic growth and quality of life. This study explores pathways for SA to achieve a sustainable electricity supply while addressing technological, policy, economic and social factors. The research will contribute to both theory and practice by advancing understanding of renewable energy integration within SA’s unique conditions, developing frameworks for analysing technical-economic-social interactions in energy transitions and extending just transition theory through practical application in coal-dependent communities. The study will provide evidence-based recommendations for policymakers on balancing grid reliability with decarbonisation goals, along with specific strategies for renewable energy integration and community-centred transition programs. Methodologically, it demonstrates an integrated approach to studying complex energy transitions while providing a model for stakeholder-inclusive research. These contributions will inform policy-making, industry practices and community engagement strategies, supporting SA’s journey towards a sustainable and equitable electricity future.

1.7. Delimitations of the study

1. Geographical Scope

- This study is limited to SA's electricity landscape, specifically focusing on grid-connected areas and renewable energy development zones.
- While regional power dynamics exist, cross-border electricity trade and international power pools are excluded.

2. Technical Scope

- The study examines utility-scale renewable electricity integration, focusing on solar PV, wind, and battery storage technologies.
- Other forms of renewable energy like geothermal, ocean energy, and small-scale applications are not included.

3. Temporal Scope

- The research examines current integration challenges and near-term solutions through 2030.
- Long-term scenarios beyond 2030 are outside the scope.

4. Stakeholder Focus

- Primary stakeholders include utility operators, renewable energy developers, regulators and affected communities.
- End-user perspectives and broader civil society views are not directly examined.

5. Policy Focus

- The study focuses on electricity sector policies directly related to renewable integration.
- Broader energy and climate policies are considered only where directly relevant to grid integration.

1.8. Definition of terms

- **Renewable electricity supply** is defined as electricity generated from natural resources that are either limitless or replenish faster than they are consumed (El Bassam, 2021).
- **Electricity access -** The term “energy access” has been used to mean “ability to use energy”, namely electricity, LPG, charcoal or some other form of energy (Brew-Hammond, 2010).
- **Hybrid systems** are co-operating units using diversified energy carriers (renewable/non-renewable) with advanced power electronics for coordination (SciDirect, 2009)
- **Sustainable electricity supply** refers to electricity generated from sustainable sources of energy, which help meet the needs present and future needs generations without compromising environmental integrity (Sorensen, 2008).
- **Just transition** is the process of shifting to a environmentally sustainable economies are promoted in a way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind (Galanis et al., 2024).
- **Grid stability** is the ability of an electrical power system to maintain a consistent balance between electricity supply and demand while keeping voltage and frequency within safe operational limits and handle fluctuations and disruptions without compromising the availability or quality of power for end-users (Sultan, 2019).

1.9. Assumptions

This study operates under the following assumptions:

1. Historical context is crucial - The study assumes that understanding the historical development of SA’s electricity sector, from its inception in 1892 to the present day, is essential for comprehending current challenges and potential solutions.

2. Electricity demand will continue to grow - Given SA’s economic expansion,

increased industrialisation, and growing population, energy demand is assumed to continue to proliferate.

3. Renewable energy is a viable alternative - While acknowledging the high capital outlay, the study assumes that renewable energy sources represent a feasible path towards electricity security and sustainability for SA.

4. Socio-economic factors are intertwined with energy issues - The study assumes that electricity access and affordability are closely linked to broader socio-economic inequalities in SA, particularly in disadvantaged communities.

5. Language and Communication - The study assumes that participants can effectively articulate their experiences and perspectives about renewable energy integration through semi-structured interviews, and that the researcher can accurately interpret and represent these perspectives.

2. LITERATURE REVIEW

2.1. Introduction

This literature review examines the complex landscape of renewable electricity integration in SA's power system. While public discourse often portrays renewable energy as a straightforward solution to the SA's electricity challenges, a deeper analysis reveals a multifaceted reality encompassing technical, economic, social and institutional dimensions. Hence, this review systematically explores four interconnected themes that collectively shape SA's energy transition pathway; the technical feasibility and geographical distribution of renewable technologies (including solar, wind, biomass and hydropower); the dynamics between rapid electrification and sustainability; the role of policy frameworks and institutional structures in enabling effective integration, the challenges of achieving a just transition in coal-dependent communities and global parallels.

Throughout this review, particular attention is paid to the unique South African context, characterised by historical inequalities in electricity access, a coal-dominated generation fleet, aging infrastructure and distinct geographical resource distribution (Baker & Phillips, 2019). By synthesising research and empirical evidence across these domains, this review seeks to reveal significant gaps between theoretical possibilities and practical implementation challenges. Therefore, the examination of these themes provides a foundation for developing realistic, context-appropriate approaches to renewable electricity integration that can enhance system reliability while supporting SA's transition to a lower-carbon electricity grid.

Having indicated the complex and multifaceted themes that are to be discussed in the literature review, this study now outlines the empirical data on grid performance as it provides critical insights into how renewable integration and grid stability challenges manifest in SA's operational context. Research by Al-Shetwi (2022) and Saha, Saleem and Roy (2023) offers statistics evidence that directly challenges simplistic narratives about renewable integration by documenting system stability trends as renewable penetration has increased. Their analysis of grid performance metrics reveals a complex relationship between renewable adoption and system reliability that must inform realistic integration strategies.

2.2. Background Discussion

SA's electricity system has distinct characteristics and challenges within this global context. SA's trajectory from initial electrification to its current state offers critical insights into contemporary challenges and future opportunities. SA's electrification trajectory reflects its socio-political history and significant achievements (Thopil, 2021):

Era & Industrial Revolution	Year	Milestone
First Industrial Revolution: (Mechanisation & Steam Power)	1880-1900	• 1882: First electric lights installed in Kimberley • 1890: First municipal electricity supply established. • 1897: First power station built to support mining industry
Second Industrial Revolution: (Mass Production & Electricity)	1900-1945	• 1906: Victoria Falls Power Company established. • 1910: Power Act passed enabling government intervention. • 1922: Electricity Act passed. • 1923: ESCOM (now Eskom) established. • 1930s: Major grid expansion begins.
Third Industrial Revolution (Automation & Computing)	1946-1990	• 1950s: Major industrial expansion and electrification • 1960s: Construction of first large coal power stations • 1970s: Nuclear power development begins • 1984: Koeberg nuclear plant commissioned • 1990: 35% national access rate
Early Democracy Period	1991-2000	• 1994: Democratic transition (36% access rate) • 1996: Constitution guarantees basic services • 2000: 66% access rate achieved
Fourth Industrial Revolution (Digital Integration & Renewables)	2001-Present	• 2010: 82% access rate • 2011: Renewable Energy IPP Program launched • 2019: Integrated Resource Plan updated • 2022: 86.5% access rate • 2024: Grid modernisation and smart systems deployment

Table 2 Electrification milestones Source: Statistics South Africa, 2023

This historical trajectory reflects broader societal transformations. The initial emphasis of coal-dominated grid expansion for mining/industry, post-apartheid electrification from 36% to 86.5% access (World Bank, 2023) and the present Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) driving wind/solar growth 6,000 MW by 2023 (Eskom, 2023).

Having established the historical and contextual background of SA's electricity system, the researcher now turns to examining the move to the transition into renewable energy and presents grid stability challenges presented by this transition. This background provides essential to South African electrification milestones

2.3. Renewable Integration and Grid Stability Challenges

Energy Sector	Output (MW)	Access rate
Coal	38,000	77%
Nuclear	1,940	4%
Renewable sources	6000	12%
Gas/Other	3000	7%

Table 3 Generation mix Source: Eskom Annual Report, 2023

SA's electricity landscape presents a complex set of challenges and contested solutions. While access rates have improved significantly from 36% in 1994 to 86.5% in 2022 (World Bank, 2023), the system faces severe constraints. The Eskom Annual Report (2023) reflects the complexity in generation mix in SA's. The integration of renewable energy sources into existing power grids presents significant challenges, particularly in systems heavily reliant on coal-fired generation and aging infrastructure (Prasad et al., 2024).

	2016	2023	Change
Solar PV	**2.31**	**0.49**	**-79%**
Wind	**1.51**	**0.42**	**-72%**
Coal	**1.03**	**1.45**	**+41%**

Table 4 South African Renewable Project Costs (R/kWh) Source: CSIR Energy Centre, 2023

Within the global context, countries facing similar challenges demonstrate diverse pathways toward integrating renewable energy. Germany, for instance, illustrates how substantial renewable penetration can be effectively managed through sophisticated grid operations and market mechanisms (Cochran, Bird, Heeter & Arent, 2012). Therefore, Germany's share of renewable electricity increased substantially, surpassing 70% renewable peak load while maintaining grid stability through advanced grid control systems and market design (Hirth & Ziegenhagen, 2013). This example highlights the importance of complementary systems and policy frameworks.

Australia is another case where rapid integration of renewable energy sources provides particularly relevant insights for SA owing to similarities highlights geographic, grid characteristics, storage and transmission needs (Cochran et al., 2012). This points to the need to successfully incorporate variable renewable electricity while maintaining system reliability through strategic energy storage deployment and grid infrastructure reinforcement.

The global and historical context exposes the opportunities and challenges confronting SA's electricity transition. However, the historical evolution of SA's electricity system offers essential insights into institutional capabilities and constraints, current performance metrics underscore the pressing need for system transformation (Buraimoh, et al., 2020). Understanding this context is essential for developing effective strategies for renewable integration while maintaining system reliability and expanding access. The experiences of other countries particularly those facing similar challenges, provide valuable insights for SA's transition pathway, underscoring the necessity for locally appropriate solutions that consider the unique characteristics of the South African electricity system.

The declining performance of existing generation infrastructure coincides with the rapidly improving economics of renewable technologies in SA. The Council for Scientific and Industrial Research (2023) documents significant cost reductions in local renewable projects, including expenses associated with environmental compliance.

Year	Renewable Share (%)	Stability	Grid Events (Annual)	Recovery Times (Min)
2018	12	High	45	2-5
2019	15	Medium	68	4-8
2020	18	Variable	89	6-12
2021	22	Declining	112	8-15
2022	25	Critical	156	10-20

Table 5 Grid evolution Source: Eskom System Operator Reports, 2023

Research by Al-Shetwi (2022) and Saha, Saleem and Roy (2023) presents compelling evidence that challenges prevailing assumptions regarding the integration of renewable energy sources. Their comprehensive analysis of SA's grid performance over the past five years reveals concerning trends related to system stability as the penetration of renewables increases. As renewable share grew, empirical data reveals declining stability as renewable share grew from 12% in 2018 to 25% in 2022 (Eskom System Operator Reports, 2023). However, while this report suggests that technological progress is crucial, it alone cannot resolve all fundamental physics-based constraints in grid operation necessitating a multifaceted approach to address the complex challenges of modern power systems (Tushar et al, 2020). Key issues being, the reduced inertia from thermal plants exacerbates vulnerability (Dudurych & Conlon, 2014) that advanced controls (e.g., AI, IoT) are critical but insufficient alone (Khalid, 2024).

Moving from these empirical observations of grid stability challenges to a broader contextual understanding, the researcher now turns to examining the technical feasibility of renewable energy technologies within the SA context. With attention to SA's unique geographical resources, existing infrastructure constraints and technical requirements for system reliability collectively shape the practical potential for renewable electricity integration.

2.4. Technical Feasibility and Geographic Resource Distribution

	Hydro	Wind	Solar PV	CSP
%	1.1	6.2	4.1	0.9
MW	600	3 443	2 287	500

Table 6 Actual nominal installed capacity Source: CSIR 2024

South Africa’s Renewable Energy Potential resources, makes it a prime candidate for large-scale renewable deployment. Currently, approximately 17,2% of the country's energy comes from renewables (CSIR, 2023). The potential renewable energy is projected to increase to 10,4GW by 2030 through projects that are under construction and those that have reached financial close (Department of Mineral Resource and Energy, 2023). This diversification positions South Africa favourably in the global energy transition.

	2025	2026	2027	2028	2029	2030
Wind (MW)	1094		1094	1094	1094	1094
Solar (MW)	560	170	1748	1748	1748	1748
Total (MW)	1654	170	2842	2842	2842	2842

Table 7 Potential additional Capacity Source: Department of Mineral Resource and Energy, 2023

2.4.1 Solar Energy

SA’s solar resources present a substantial opportunity for energy system transformation, with approximately 2,500 hours of sunshine annually, with solar radiation levels of 4.5 to 6.5 kWh/m² and a potential exceeding 6,000 GW (Aderemi et al., 2017). This exceptional resource endowment particularly in the Northern Cape province creates significant potential for both utility-scale and distributed solar applications. The solar PV market is projected to grow up to 7,722GW by 2030) through business initiatives that are inprogress or financially closed. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has added 2,3 GW of Solar capacity via private investments up to date and 6,2GW from customer PV resources. However, recent research challenges simplistic assumptions regarding solar energy's capacity as a comprehensive solution. While solar capacity has grown significantly, reaching 1,059 gigawatts globally by 2021 several challenges persist (Alami et al.,2022). These include the effects of shading, soiling, and temperature fluctuations on photovoltaic performance (Alami et al., 2022). Despite these challenges, solar energy continues to offer environmental and economic benefits, including reduced greenhouse gas emissions and job creation (Sonkar, Pandey & Verma, 2024).

Several significant integration challenges that must be addressed for effective solar deployment. These include technical issues like non-dispatchability, power quality concerns, and grid stability problems (Shafiullah, Ahmed, & Al-Sulaiman, 2022); Mohammadi & Neagoe, 2020). However, to ensure reliable supply, the intermittent nature of solar generation requires sophisticated storage solutions, particularly during evening peak demand periods (Sharrma, Prasad & Pajany, 2021). Second, grid stability concerns emerge during periods of low solar generation, necessitating complementary generation or storage technologies. Third, the Intermittency, transmission costs from resource-rich regions (Boateng & Mhangara, 2023). Finally, comprehensive system costs extend well beyond panel installation to include grid connection, control systems, and backup capacity (Morey, Gupta, Garg & Kumar, 2023).

These findings align with Al-Shetwi et al.'s (2020) technical analysis of renewable grid integration challenges in developing economies. Their research emphasizes that successful solar integration depends on both technical solutions and appropriate regulatory frameworks, particularly regarding grid codes and connection standards. Collectively, these studies demonstrate that while solar energy presents significant potential for SA, its effective implementation necessitates careful consideration of system-wide implications and supporting infrastructure.

2.4.2 Wind Energy

Wind energy development in SA presents both promising opportunities and distinct challenges for the country's energy transition. The Wind Atlas for South

Africa (WASA) project has identified significant wind resources particularly in coastal regions of the Western and Eastern Cape provinces (Ayodele, Jimoh, Munda & Agee, 2013). These areas demonstrate capacity factors ranging from 35-45%, comparable to some of the world's best wind resources (Adefarati & Obikoya, 2019). Wind Energy offer 5,470 GW of potential by 2030 (DMRE, 2023), with wind already contributing 6,2% of renewable generation (CSRI, 2024). The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has added 3,7 GW of wind capacity via private investments up to date.

Mukonza & Nhamo, (2018) identify several critical considerations for wind integration in the South African context. First, it shows that SA has put in place critical policies, institutions and programmes for wind energy uptake. Among key policy documents and policies are the White Paper on Energy (1998), Renewable Energy White Paper (2003), Energy Act of 2008, and National Climate Change Response White Paper (2011). Second, wind generation patterns in SA exhibit significant seasonal and diurnal variability with implications for grid stability and system planning. Third, integration costs extend beyond direct generation expenses to include grid reinforcement, balancing services and system operation adaptations (Aunedi, et al., (2016). Finally, environmental and land-use considerations, including bird migration paths and competing agricultural uses, influence sitting decisions.

The evidence suggests that wind energy represents a valuable component of SA’s renewable energy portfolio, particularly when deployed as part of a diversified generation mix with appropriate supporting infrastructure and operational practices (Mukonza & Nhamo, 2018; Adebiyi, & Moloi, 2024).

2.4.3 Biomass and Hydropower

The role of biomass and hydropower in SA’s energy transition represents a complex interplay of opportunities and constraints influenced by the country’s distinctive geographical and climatic conditions. These technologies offer valuable dispatchable renewable energy options, but their potential is substantially limited by resource availability and environmental considerations (Angliviel de La Beaumelle et al., 2023).

Biomass energy presents a promising solution with substantial potential from agricultural residues and invasive alien plants. Crop residues alone could generate an estimated 13.5 million tonnes of biomass annually (Barahira, Okudoh and Eloka-Eboka, 2021) while invasive alien plants could provide 167 million tonnes of woody biomass (Rawat, Singh & Tekleyohannes, 2024). These resources could support both electricity generation and biofuel production offering rural development opportunities and waste management benefits. However, several significant constraints limit large-scale deployment. The competition for agricultural land emerges as a critical concern, particularly in a nation where food security remains a pressing issue. Additionally, the logistical challenges of biomass collection, transportation and processing create economic barriers, especially in remote areas (Keefe, Anderson, Hogland & Muhlenfeld, 2014).

Hydropower resources in SA are relatively limited compared to other African nations with current installed capacity of approximately 3,600 MW, including 2,732 MW of pumped storage (van Dongen & Bekker, 2020). Climate change may further impact the viability of large hydroelectric schemes in Southern Africa (Mukheibir, 2013) with projected rainfall pattern changes potentially affecting water availability for power generation. Despite these challenges, there is renewed interest in regional small hydropower (SHP) development (Klunne, 2013). This has led to SA identifying approximately 8,000 potential SHP sites in KwaZulu-Natal and Eastern Cape provinces (Ilupeju & Inambao, 2014). Hence, SHP is considered cost-effective and environmentally friendly, offering opportunities for both grid-connected and off-grid applications especially for the farming community. Furthermore, SA capitalizes on hydropower import, currently SA receives power from Mozambuque (Cashora-Basa) and SA has entered into a treaty with the Democratic Republic of Congo (Grand Ingula Project) as a potential addition to the energy generation.

The integration of these technologies into SA’s energy mix requires careful consideration of resource availability, environmental impacts and socioeconomic factors. Their deployment should be strategically planned as part of a diversified renewable energy portfolio that leverages the unique advantages of each technology while recognising their limitations.

2.4.4 Integrated Approach

The literature increasingly underscores that SA’s renewable energy future relies not on individual technologies functioning in isolation but on their systematic integration into a cohesive framework. Orikpete, Ikemba & Ewim, (2023) provides compelling evidence that the successful deployment of renewable energy necessitates a nuanced understanding of how various technologies complement one another and interact with existing infrastructure. This analysis asserts that mere enhancement of grid infrastructure maybe inadequate to address integration challenges. Therefore, the discourse surrounding this issue extends to the development of smart grid technologies, the implementation of effective energy storage solutions and the establishment of robust demand-side management strategies.

Integrating renewable energy sources into existing power systems is crucial for enhancing climate resilience and mitigating climate change impacts (Ekechukwu & Simpa, 2024). Therefore, successful integration requires addressing technical, economic and regulatory challenges (Khalid, 2024). Regarding the technical perspective, it is important to note that advanced technologies like artificial intelligence (AI) and internet of things (IoT) are essential for managing the variability of renewable sources (Khalid, 2024). Whereas, policy frameworks are pivotal, necessitating supportive regulations, increased R&D funding, and public-private partnerships (Khalid, 2024; Cochran et al., 2012).

The integration of high levels of renewable energy into power grids presents significant operational challenges due to the intermittent nature of these sources. Key issues include maintaining grid stability, frequency control, and voltage regulation (Al-Shetwi et al., 2020). To address these challenges, advanced forecasting techniques, flexible generation and demand response strategies are crucial (Bird, Milligan & Lew, 2013).

The examination of renewable technologies and their integration requirements leads to a proposition regarding the diversified configuration of these resources for the South African context. This proposition synthesises insights about geographic resource distribution, technology characteristics and system requirements to address the research question concerning effective renewable combinations.

2.4.5 Proposition 1

A diversified energy mix, hybrid systems (solar, wind, storage) maximize capacity factors and reduce reliance on single sources. Based on SA's geographic distribution of solar and wind resources, will enhance grid reliability while advancing the country's decarbonisation objectives.

2.5. What combination of utility-scale solar PV, wind energy, and grid-scale battery storage technologies can most effectively balance SA's decarbonisation objectives with grid reliability, leveraging the country's geographic distribution of solar and wind resources?

2.5.1 Current Electrification Status

Since the end of apartheid in 1994, SA has made significant strides in electrification and basic service delivery particularly benefiting previously disadvantaged communities (Kroth, Larcinese & Wehner, 2016). The key implication drawn from this is that the Integrated National Electrification Programme has been notably successful in increasing access to electricity for the poor and potentially influencing voting patterns (Tinto & Banda, 2005). On the contrary, progress has been uneven across various socio-economic indicators (Rao & Pachauri, 2017).

Recent research Gamette, Odhiambo and Asongu, (2024) highlights persistent disparities in electricity access across urban and rural areas in developing countries, particularly in sub-Saharan Africa. While urban electrification rates have reached 92.8%, rural areas lag at 75.3% with informal settlements facing even greater challenges at 63.4% (Besner, Mehta & Zörner, 2023). Consequently, factors influencing these disparities include population growth rates, electricity consumption per capita and oil dependency (Alegre-Bravo & Anderson, 2023). Nonetheless, the pace of electrification must triple to achieve universal access by 2030.

The present state of electrification in SA reflects a narrative of notable advancements juxtaposed with emerging challenges. Although the SA has achieved considerable progress in expanding access to electricity, issues on quality, reliability and affordability persistently influence the electrification landscape (Longe, 2020). This is worth noting as future success hinges on the capacity to confront these challenges while utilising innovative technologies and methodologies to ensure sustainable and equitable access to electricity for all citizens of SA (Moghayedi, Hübner & Michell, 2023).

The next section below examines emerging strategies that aim to accelerate electricity access while enhancing sustainability. These approaches represent a significant evolution from traditional grid-centric models toward more diverse and context-sensitive solutions.

2.5.2 Sustainable Electrification Strategies

The evolution of sustainable electrification strategies in SA illustrates a complex interplay of technological innovation, policy development and social transformation. Recent research highlights a significant shift in electrification strategies, moving from grid-centric approaches to more diverse, sustainable solutions. This change recognises the urgency of providing access while ensuring long-term sustainability (González-García, Díaz-Pastor & Moreno-Romero, 2023). The new approach integrates grid extension, mini-grids and standalone systems, tailored to specific contexts and demand levels (Mentis et al., 2017). Successful implementation requires comprehensive governance, involving multiple stakeholders and considering macro and micro level factors (González-García et al., 2023).

Traditional grid extension in SA faces challenges, prompting the need for innovative electrification solutions. While grid expansion remains crucial, it struggles to meet growing demand and population needs (Rawn & Louie, 2017). Figure 2 demonstrates the grid plan for the approved REIPPP solar and wind plants in the bid SINGLE WINDOWs (Eskom, 2024 and DMRE, 2023) that requires $12bn grid investments by 2030 (World bank group, 2025). Figure 3 indicates the generation connection capacity in the country supply areas. The Northern Cape power corridors is constrained and cannot accomodate additional generation further to what has already been approved. Substantial upstream network strengthening will therefore be required to facilitate new generation capacity.

The GCCA has mapped the available grid capacity to connect new generation projects (renewables, gas, etc.). It has identified the grid constraints per province that may delay connections.

Aspect	Details
Available Capacity	5.5GW total remaining grid capacity
Constrained Zones	Northern Cape (Solar): 98% capacity occupied, new projects require grid upgrades. Eastern Cape (Wind) capacity is 85% occupied
Priority Areas	Mpumalanga: New capacity for coal-to-renewables repowering. KwaZulu-Natal: Gas plant opportunities.

Table 8 Key findings from GCCA 2023 Source Eskom: 2024

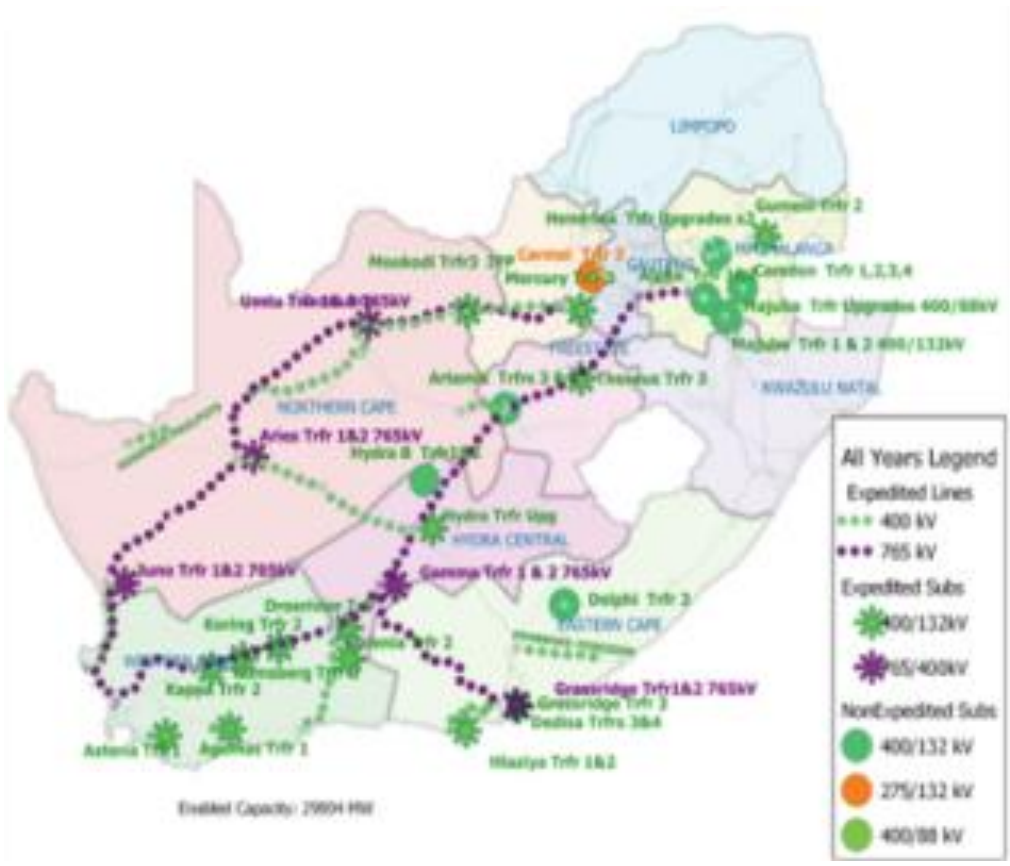

Figure 2 Grid planning Source: IRP 2023

Off-grid alternatives like solar home systems and mini-grids offer potential "leapfrogging" opportunities but encounter distribution, affordability and regulatory hurdles (Rawn & Louie, 2017). Mini grids offer reliable off-grid power for remote communities. South Africa's mini-grid development, synthesizing policy, projects, challenges, and future directions. Renewable energy-powered minigrids present a promising solution, with a case study in rural Jozini municipality demonstrating lower costs and zero emissions compared to the national grid (Longe, et al., 2019). Smart grid technologies could address efficiency and management issues, though implementation faces challenges requiring government support and stakeholder involvement (Zikalala & Chowdhury, 2015).

Energy storage has emerged as a critical facilitator of sustainable electrification. The Energy Storage Association of South Africa (2023) documents how storage solutions, ranging from grid-scale installations to community-level systems, effectively address the intermittency challenges associated with renewable energy while enhancing grid stability. These storage systems perform multiple functions, including load shifting and frequency regulation, thus bridging the gap between variable renewable generation and consistent electricity demand.

The pathway to successful electrification necessitates the meticulous integration of various elements. Even historic evidence indicates that the most effective strategies amalgamate technological innovation with robust policy support and active community engagement (Costello, 2011). Nevertheless, efforts towards grid modernisation must operate in conjunction with distributed solutions, while storage technologies and demand management programs contribute to optimising system performance (Baby & Jayakumar, 2020). Furthermore, financial mechanisms must align with technical requirements and community capacities.

2.5.3 Energy justice theory

The theoretical foundations of SA's energy transition exemplify a compelling intersection of established frameworks and emerging paradigms. Recent research by (Segura, 2024) has enhanced the understanding of energy transitions, particularly in developing economies. Thus, energy transitions involve technological, economic, social and political processes (Buchanan, 2017; Segura, 2024). These transitions encompass explicit changes in energy systems and implicit shifts in energy security, geopolitics, and governance (Smith & Stirling, 2010).

Researchers emphasise the importance of multidisciplinary approaches, integrating qualitative and quantitative analyses to study these transitions (Buchanan, 2017; Segura, 2024). Policy and governance are crucial in shaping low-carbon transitions as private incentives alone are insufficient (Buchanan, 2017). Hence, a socio-technological systems perspective, such as Actor-Network Theory, can provide valuable insights into the complex dynamics of energy transitions in emerging markets (Chipangamate et al., 2023). Understanding these multifaceted challenges is essential for policymakers and practitioners to navigate energy transitions effectively.

2.5.4 Rapid Electrification vs Sustainability

The perceived tension between rapid electrification and sustainability within SA’s energy landscape has evolved significantly in recent academic discourse (Ting, 2021). Therefore, the proliferation of contemporary research in reframing these issues highlights their potential synergies and complementary nature rather than viewing them as competing priorities (Omahne, Knez & Obrecht, 2021).

Shifting Paradigms

While rapid electrification is crucial for improving quality of life and economic development it must be balanced with environmental sustainability (Sahu, Shandilya, Bhardwaj & Azad, 2014). As a result, evidence indicates that integrating sustainability considerations into electrification planning can enhance access objectives in developing regions (Cuenca-Enrique, del-Río-Carazo, Acquila-Natale & Iglesias-Pradas, 2024). Thereupon, sustainable and decentralised electricity options particularly solar and wind power offer promising solutions for addressing energy poverty (Muchapondwa, Jeuland & Shimeles, 2021). Hence, the assumption that environmental sustainability must be sacrificed for rapid electrification represents a false choice. Therefore, evidence demonstrates that renewable energy technologies when properly integrated with existing infrastructure, can accelerate access while reducing both costs and environmental impacts (Thiam, 2011; Uzondu & Joseph, 2024).

The potential synergies between rapid electrification and sustainability objectives cannot be realised without supportive policy and regulatory frameworks (Bisaga et al., 2021). These institutional structures play a crucial role in either enabling or constraining the deployment of sustainable electrification approaches shaping both the pace and character of SA’s energy transition.

2.5.5 Policy and Regulatory Frameworks

The evolution of SA’s energy policy and regulatory frameworks presents a compelling narrative of transformation, adaptation and ongoing challenges in pursuing sustainable energy development. Beginning with the foundational White Paper on Energy Policy in 1998, this progression encompasses contemporary integrated approaches (Mukonza & Nhamo, 2018). It reflects an increasingly sophisticated comprehension of the complexities inherent in transforming energy systems.

SA’s energy policy landscape has undergone significant transformation since the end of apartheid, characterised by three distinct phases. The first phase focused on establishing a legislative framework for renewable energy investment to achieve 10,000 GWh by 2013 and move towards a low-carbon economy (Nhamo & Ho, 2011). The second phase emphasised energy efficiency, targeting a 12% reduction in final energy demand by 2015 (Nhamo & Bimha, 2011). The third phase saw the emergence of a renewable energy sector embedded within the country's unique electricity system and political economy (Baker & Philips, 2019). Policy development has been influenced throughout these phases by the apartheid legacy and the structure of SA’s energy system (Marquard, 2006). While progress has been made in renewable energy and energy efficiency policies, challenges remain in addressing energy poverty and global warming necessitating measures that tackle the fundamental structure of the energy system (Marquard, 2006).

The analysis of electrification strategies, sustainability considerations and policy frameworks suggest a pathway for accelerating both access and decarbonisation through strategic renewable integration. This leads to a proposition that addresses the research question on expanding reliable electricity access while advancing climate objectives.

2.5.6 Proposition 2

The phased integration of decentralised renewable energy systems coupled with modernisation of transmission infrastructure will significantly accelerate equitable electricity access and support SA's decarbonisation efforts in rural and peri-urban regions.

2.6. How can phased integration of decentralised renewable energy systems (e.g., mini-grids, solar home systems) and modernisation of transmission infrastructure accelerate equitable electricity access and decarbonisation in SA's rural and peri-urban regions?

2.6.1 Principal-Agent Theory

The dynamics between government authorities and private investors in SA's sustainable energy sector reveal a complex web of relationships, expectations and often conflicting interests. As an illustration, the Principal-Agent Theory provides a compelling framework for understanding these relationships and their implications for sustainable energy investment (Rosenberg, 2017). Through this theoretical lens, one can understand why attractive investment opportunities occasionally fail to materialise and how policy interventions may effectively bridge the gap between public objectives and private actions (Rangan, Samii & Van Wassenhove, 2006).

Contract design emerges as a critical instrument for managing principal-agent relationships. The importance of well-crafted contracts in bridging the gap between public policy objectives and private sector interests is critical (Zerunyan, 2019). This calls attention to successful contracts striking a balance between providing investor certainty and allowing for policy flexibility, thereby establishing frameworks capable of adapting to changing circumstances while preserving essential stability for investors. This comprehensive understanding of principal-agent dynamics provides valuable insights for policymakers aiming to promote private-sector investment in sustainable energy. It indicates that success is not solely dependent on the development of increasingly larger incentives but rather on the meticulous design of frameworks that align public and private interests while effectively managing the inherent complexities of these relationships (Olajiga et al., 2024).

While Principal-Agent Theory illuminates the dynamics between specific actors in the energy sector, Institutional Theory broadens our perspective to examine how established organisational patterns, cultural norms and formal regulations collectively shape the trajectory of SA’s energy transition. These complementary theoretical lenses help explain both individual relationships and broader structural constraints.

2.6.2 Institutional Theory

The narrative of institutional transformation within SA’s energy sector exemplifies a significant struggle between established structures and emerging paradigms. Utilising the framework of Institutional Theory, one can discern how deeply ingrained organisational patterns, cultural norms and formal regulations influence the trajectory of sustainable energy development (Horak, et al., 2018). The process of institutional change follows multiple pathways in SA’s energy sector. This highlights how successful institutional change requires careful attention to both formal rules and informal practices suggesting that policy interventions ignoring existing institutional dynamics often fail regardless of their technical merit (Blanco et al., 2022).

Power dynamics emerge as a crucial theme as they illuminate how institutional change in SA’s energy sector reflects complex relationships between established interests and emerging stakeholders (Baker, 2011). This means that control over resources, decision-making authority and access to information emerge as key dimensions of power that shape institutional development. Understanding these power dynamics proves crucial for effective policy implementation. This deeper understanding of institutional dynamics offers valuable insights for policymakers promoting sustainable energy development. It suggests that successful transformation requires attention to formal rules and structures and the complex web of informal practices, cultural norms, and power relationships that shape institutional behavior.

2.6.3 Current State of Sustainable Energy Investment in South Africa

The landscape of sustainable energy investment in SA presents a complex scenario characterised by considerable growth potential tempered by enduring challenges. Recent data and research indicate both promising trends and significant obstacles in the nation’s advancement toward sustainable energy development.

Investment Trends and Patterns

According to the International Renewable Energy Agency (IRENA, 2023), SA has attracted approximately R209 billion in renewable energy investment between 2011 and 2023, with significant acceleration in recent years:

Year	Amount
2019-2020	R34.7 billion
2020-2021	R42.3 billion
2021-2022	R56.2 billion
2022-2023	R76.5 billion

Table 9 Investment trends & patterns Source: International Renewable Energy Agency (IRENA
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Economic Realities and Hidden Costs

The economic dimension of renewable integration reveals equally complex challenges. While advocates frequently state the dramatic decline in solar and wind technology costs, Energy Economics Institute report 2023 groundbreaking analysis exposes a more nuanced economic reality. Their comprehensive cost assessment reveals previously underappreciated system integration expenses:

Cost Component	Initial Cost	Actual Cost	Hidden Cost
Generation Equipment	R1.0bn	R1.0bn	Equipment logistics
Backup Systems	R0.30bn	R0.65bn	Reliability requirements
Control Systems	R0.25bn	R0.40bn	Software complexity
System Balancing	R0.20bn	R0.55bn	Operational demands
Total System Cost	R2.20bn	R3.45bn	+57% overall increase

Table 10 Renewable energy integration cost analysis Source: Energy Economics Institute, 2023

This comprehensive cost analysis fundamentally challenges reductive economic narratives surrounding renewable energy integration. The research demonstrates that initial cost estimates frequently fail to encapsulate the full complexity of system integration requirements. The true cost of renewable integration extends far beyond generation technology prices, encompassing a complex web of system upgrades and operational changes. The key implication drawn from this is that success does not reside in merely balancing competing priorities but in identifying and leveraging synergies between these objectives. Hence evidence suggests that sustainable approaches can frequently accelerate electrification while simultaneously yielding additional environmental and social benefits (González-García et al., 2023).

The investment landscape described above with its opportunities and persistent challenges has directly influenced the evolution of policy measures and incentives designed to accelerate renewable deployment. Policy interventions represent deliberate attempts to address market barriers, reduce investment risks and channel capital toward priority areas within SA’s energy transition.

2.6.4 Policy Measures and Incentives

The evolution of SA's policy measures and incentives for sustainable energy investment tells a story of innovation, learning and adaptation in the face of complex challenges. Through years of experimentation and refinement, SA has developed a sophisticated framework of policies and incentives though their effectiveness continues to be tested by emerging market dynamics and implementation challenges (Nokele, 2022).

Arguably, the REIPPPP launched in 2011 stands as perhaps the most significant policy innovation in SA's sustainable energy landscape. As a result, this program marked a fundamental shift in how SA approached renewable energy development. Moving away from feed-in tariffs, the REIPPPP introduced a competitive bidding system that has since become a model studied by other developing nations (Eberhard, Kolker & Leigland, 2014). Since its inception in 2011, the program has procured over 6,300 MW of renewable energy capacity, attracting approximately US$20.5 billion in private investment (Eberhard & Naude, 2016). The REIPPPP's achievements have made it a model for other sub-Saharan African countries demonstrating that well-designed auction programs can effectively drive private investment in renewable energy projects (Kruger & Eberhard, 2018). This evolving landscape suggests that successful policy measures and incentives must be both robust and adaptable. They need to provide sufficient certainty to attract investment while maintaining flexibility to respond to changing market conditions. Most crucially, they must be backed by strong institutional capacity to ensure effective implementation.

The economic and institutional analyses converge on the critical role of policy frameworks in shaping transition outcomes, particularly for vulnerable communities. This insight informs a proposition regarding how targeted interventions can support just transition objectives while fostering economic diversification in coal-dependent regions.

2.6.5 Proposition 3

Implementing targeted policy frameworks and localised initiatives, such as skills retraining programs and community- owned renewable projects will be essential for ensuring a just transition in coal-dependent communities in Mpumalanga while enabling economic diversification through the renewable energy sector.

2.7. What policy frameworks and localised initiatives (e.g., skills retraining, community-owned renewable projects) are critical to ensuring a just transition for coal-dependent communities such as Mpumalanga while fostering economic diversification through renewable energy sectors?

2.7.1 Just Transition Theory

The concept of Just Transition has emerged as a significant theoretical framework for comprehending and navigating SA's intricate transition from coal dependency to sustainable energy. This theoretical lens elucidates the profound interconnections between the transformation of energy systems and critical issues of social justice, economic equity and community resilience.

Scholarship by Wilgosh, Sorman and Barcena, (2022) demonstrate how Just Transition Theory (JTT) has evolved from its labour movement origins to encompass broader societal concerns in the South African context. Their research reveals that successful energy transitions must address not only technological and economic changes but also the profound social and cultural implications for coal-dependent communities. The Just Transition framework in SA transcends mere worker protection, extending to encompass entire communities whose identities, economies and social structures have been shaped by generations of coal mining and power generation. This broader conceptualisation necessitates more comprehensive approaches to transition management. (Otlhogile & Shirley, 2023).

The concept of Just Transition (JT) in SA’s coal-dependent economy encompasses four key pillars: depth and urgency, scale and scope, identity and inclusion, and material equity (Wilgosh et al., 2022). SA faces significant challenges in transitioning from coal to renewables, particularly in the Mpumalanga Coal-Belt region, where over 100,000 workers are employed in coal-related industries (Nel, Marais & Mqotyana, 2023). Therefore, a just transition requires balancing human well-being with sustainability goals, including decarbonisation and ecosystem restoration (Swilling, Musango & Wakeford, 2016). However, socio-political constraints, such as the Renewable Independent Power Producer Programme (REI4P) exacerbate energy vulnerabilities and misrecognition of affected communities (Mirzania, Gordon, Balta-Ozkan, Sayan & Marais, 2023). To achieve a just energy transition, SA must address techno-economic, socio-political and socio-technical barriers while realigning its Minerals Energy Complex towards renewable electrification, community empowerment, and sustainable socio-economic structures (Mirzania et al., 2023).

While Just Transition Theory focuses primarily on labour and community transitions, Energy Justice Theory broadens this perspective by examining how energy systems fundamentally shape and reflect societal power relations and equity outcomes. These complementary frameworks together provide a more comprehensive lens for evaluating SA’s coal-to-renewable transition.

2.7.2 Energy Justice Theory

Energy Justice Theory (EJT) has evolved to encompass three fundamental dimensions: distributional, procedural and recognition justice (Lee & Byrne, 47 2019). This “three-tenet framework” has become the predominant approach in energy justice research (Wood, 2023). However, critics argue that this framework omits explanatory interconnections between dimensions and conceals the depth of each dimension (Wood, 2023). Researchers have proposed expanding the conceptual basis of energy justice by considering institutionalised tendencies of modern energy systems and their connections to political, economic and technical ideologies (Lee & Byrne, 2019). The application of energy justice in developing countries has highlighted themes such as decentralisation, institutional instability and marginalised communities (Lacey-Barnacle, Robison & Foulds, 2020). To address challenges in the three-tenet model, a pragmatic and pluralist dialogue model based on the commonwealth model has been proposed that aims to create moral legitimacy in the face of plural demands for energy justice (Laes, Bombaerts & Spahn, 2023). This evidence suggests that EJT provides crucial insights for policymakers and practitioners working to create more equitable energy systems. It emphasises that technical solutions must be accompanied by careful attention to social equity, procedural fairness, and recognition of diverse needs and experiences.

Turning to the specific context of SA's coal-renewable relationship. The country's entrenched coal dependence presents distinct challenges for implementing the justice principles outlined above, requiring careful consideration of both economic dependencies and community identities.

2.7.3 Coal Dependency vs Renewable Energy

SA's entrenched relationship with coal presents a multifaceted narrative characterised by economic dependency, social identity and environmental challenges. Studies conducted by Shongwe, (2018) indicates that coal mining plays a crucial role in SA's economy, providing 85% of the country's electricity and supporting numerous jobs. The coal sector's economic significance extends beyond pure statistics, embedding itself deeply in regional identities and social structures. Merven, Hartley & Arndt, (2019) indicate that renewable energy has significant potential to drive economic growth and job creation in SA while reducing greenhouse gas emissions. Therefore, transitioning to renewable energy could positively impact GDP and employment with renewable technologies becoming the largest contributor to electricity generation under least-cost planning.

The coal dependency patterns described above translate directly into employment vulnerabilities as SA's energy system evolves. Understanding these employment impacts and potential economic restructuring pathways is essential for developing effective transition strategies that protect livelihoods while enabling decarbonisation.

2.7.4 Job Losses and Economic Restructuring

The energy transition away from coal has complex impacts on employment in coal-dependent regions, revealing three distinct waves of effects. Initially, there is a risk of lock-in and persistence of the status quo (Nacke, Cherp & Jewell, 2022). The second wave involves potential backlash from directly affected companies and workers (Nacke et al., 2022), highlighting the need for just transition policies to protect vulnerable groups (Harrahill & Douglas, 2019). The final wave risks regional despondence emphasising the importance of community-based decision-making in the decommissioning process (Tarekegne, Kazimierczuk & O'Neil, 2022). To address these challenges, policymakers should focus on technical assistance, cross-partnership engagement, and financial aid (Tarekegne et al., 2021). Additionally, gradual closure, guidelines for thermal power plant areas and shifts towards alternative livelihoods are suggested to mitigate job losses (Singh & Swarnakar, 2023). For this reason, effective policy sequencing and a framework for successful just transition are crucial for managing these employment impacts (Nacke et al., 2022; Harrahill & Douglas, 2019).

Addressing the employment and economic challenges identified requires deliberate policy interventions and governance structures that can guide the transition process. These institutional arrangements play a crucial role in determining whether SA's energy transition exacerbates inequalities or creates opportunities for more inclusive development.

2.7.5 Policy Approaches and Governance

The governance of energy transition requires sophisticated policy frameworks addressing multiple objectives simultaneously. Key principles for effective energy policies include complementarity, transparency and adaptability (Pahle et al., 2021). These policies should balance different goals, track impacts comprehensively and adapt to changing objectives over time. Although regional governance plays a crucial role in energy transition, it is necessary to involve structural characteristics of actor networks, actor characteristics and regional governance arrangements (Hoppe & Miedema, 2020). On the contrary, social imbalances and governance quality significantly influence energy transition with social imbalances dampening positive impacts and good governance augmenting them (Sinha, Bekiros, Hussain, Nguyen & Khan, 2023). This approach requires changes in governance patterns to effectively address the complex challenges of energy transition and sustainable development.

While broader policy frameworks establish the direction for transition, targeted social protection measures are essential for supporting individuals and communities through the immediate disruptions of energy system change. These protection mechanisms complement structural policies by addressing immediate vulnerabilities while longer-term economic diversification develops.

2.7.6 Social Protection Measures

Beyond broader structural policies, effective just transition approaches require targeted social protection measures that address immediate vulnerabilities while longer-term economic transformations unfold. Harrahill and Douglas (2019) emphasise that successful transitions must include comprehensive safety nets that protect workers and communities during periods of economic adjustment. These measures typically encompass direct income support, retraining programs and community development initiatives. In the South African context, (Nel et al., 2023) document how coal-dependent communities in Mpumalanga face particular vulnerabilities due to limited economic diversification and high dependency ratios, requiring customised protection approaches.

The design of social protection measures must balance immediate relief with long-term development objectives. Moreover, (Singh and Swarnakar, 2023) identify three key components of effective protection frameworks: gradual phase-out schedules for fossil fuel facilities that allow for adaptation planning; comprehensive retraining programs that align with emerging economic opportunities; and community-based support systems that address both individual and collective needs. According to (Swilling et al., 2016), these measures are most effective when they acknowledge existing social assets and community capabilities rather than imposing externally designed solutions.

These insights suggest that SA's approach to social protection during energy transition should be both comprehensive in scope and collaborative in governance, recognising the diverse needs of affected stakeholders while building on existing community strengths

2.8. Conclusion of Literature Review

The comprehensive literature review of SA's energy transition reveals a multifaceted transformation spanning technical, economic, social and institutional dimensions, challenging conventional assumptions that pit rapid electrification against sustainability. Central to this process are institutional frameworks and coordination mechanisms which contemporary research identifies as pivotal for enabling effective policy implementation and market development. Complementing these institutional factors, private sector investment patterns highlight both emerging opportunities and systemic barriers in advancing the transition. Studies underscore that achieving equitable outcomes particularly for coal-dependent communities disproportionately affected by structural shifts demands addressing not just technical or economic hurdles but also deeply rooted social and cultural dynamics. Synthesising these findings, the evidence suggests that while SA faces formidable challenges, a viable pathway lies in integrating technical solutions with proactive equity measures, reinforced by adaptive institutions and innovative policy design to balance competing priorities.

RQ #	State Research Question	Prop	State Proposition
1	What combination of utility- scale solar PV, wind energy, and grid-scale battery storage technologies can most effectively balance SA's decarbonisation objectives with grid reliability, leveraging the country's geographic distribution of solar and wind resources?	1	A diversified energy mix, hybrid systems (solar, wind, storage) maximize capacity factors and reduce reliance on single sources. Based on SA's geographic distribution of solar and wind resources, will enhance grid reliability while advancing the country's decarbonisation objectives.
2	How can phased integration of decentralised renewable energy systems (e.g., mini- grids, solar home systems) and modernisation of transmission infrastructure accelerate equitable electricity access and decarbonisation in SA's rural and peri-urban regions?	2	The phased integration of decentralised renewable energy systems coupled with modernisation of transmission infrastructure will significantly accelerate equitable electricity access and support SA's decarbonisation efforts in rural and peri-urban regions.
3	What policy frameworks and localised initiatives are critical to ensuring a just transition for coal-dependent communities while fostering economic diversification through renewable energy sectors?	3	Implementing targeted policy frameworks and localised initiatives, such as skills retraining programs and community-owned renewable projects will be essential for ensuring a just transition in coal-dependent communities such as Mpumalanga while enabling economic diversification through the renewable energy sector.

Table 11 Consistency table: research questions and propositions

3. RESEARCH METHODOLOGY

The research methodology outlines the constructivist research philosophy that informed the study, the qualitative research approach and design and the case study design that provided a framework for in-depth exploration. Furthermore, the chapter details the data collection methods focusing on semi-structured interviews with energy sector stakeholders and describe the purposive and snowball sampling strategies used to recruit participants. Additionally, the chapter covers the thematic analysis process employed to identify patterns in the data, the measures taken to ensure trustworthiness and credibility and the ethical considerations that guided the research process throughout all stages of the study.

3.1. Research philosophy

This study adopted a constructivist paradigm, which holds that reality is socially constructed and that individuals develop subjective meanings of their experiences through interaction with others (Creswell & Poth, 2016). This paradigm is particularly appropriate for exploring SA's energy transition since stakeholders' perceptions, experiences and interpretations of energy issues are shaped by their social, cultural and professional contexts. Thus, the constructivist worldview acknowledges that meaning is negotiated socially and historically through interaction with others (Lincoln & Guba, 1985). In the context of this study, this means recognising that stakeholders' understanding of renewable electricity integration is influenced by their positions within the energy sector, their professional backgrounds and their experiences with existing energy systems.

3.2. Research approach

The adoption of an inductive approach for this study was grounded in the principles of interpretivism. In interpretivism, the foundational belief that reality is socially constructed and shaped by individual experiences aligns closely with the inductive method's emphasis on deriving conclusions from observed patterns, similarities and regularities (Hiller, 2016). The rationale for embracing the inductive approach within the framework of interpretivism is multi-faceted. By focusing on observed patterns, the approach lends itself to a nuanced exploration of the participants' experiences, capturing the dynamics that might not be evident through a more deductive lens (Saunders et al., 2012).

Research design

A research design serves as a comprehensive blueprint that addresses the questions researchers seek to answer while also effectively managing the potential challenges that may arise during the research process (Creswell & Poth, 2016). Therefore, this study employed a generic qualitative research design using a case study approach. This design was selected to obtain an in-depth understanding of the complex energy issues in SA through thorough examination and analysis of different phenomena. The case study design allowed the researcher to probe deeply into participants' responses regarding energy issues while maintaining a holistic view of the context (Yin, 2009).

The case study approach had several advantages for this research:

- It enabled detailed investigation of renewable energy integration within the real-world context of SA's electricity system.
- It allowed examination of multiple stakeholder perspectives and experiences.
- It facilitated exploration of complex relationships between technical, economic and social factors.

However, as noted by (Creswell & Creswell 2017), case studies can be time-consuming to conduct properly. This limitation was managed through careful planning and scheduling of data collection activities.

3.3. Data collection methods

Semi-structured interviews were used to reveal information about participants' experiences on renewable energy issues. Thus, semi-structured interviews permit room for interviewees to answer questions in ways that tap into their own experience of being affected by renewable energy integration rather than explicitly leading them towards answering questions based on the literature (Raworth et al., 2012). Hence, research questions were designed to be broad in scope so that interviewees constructed their meaning through discussion.

3.4. Population and sample

3.4.1 Population

The population for this qualitative study on renewable electricity integration in SA encompasses diverse stakeholders essential to understanding the country's renewable energy landscape. This demographic included South African citizens affected by renewable energy landscape, particularly those working from both traditional and renewable energy sectors; government officials at various levels involved in energy policy formulation; representatives from the private sector, including energy companies and major energy-consuming industries; civil society organisations and NGOs engaged in energy access and environmental issues; academic experts in relevant fields; international stakeholders, such as development agencies and foreign investors; and youth pursuing studies or careers in energy-related disciplines. This diverse population reflects the multifaceted nature of SA's energy challenges and opportunities to capture a comprehensive understanding of pathways towards sustainable renewable energy supply by considering a wide range of perspectives and experiences.

3.4.2 Sample and Sampling Method

This study employed purposive and snowball sampling methods to identify and recruit participants. Purposive sampling is a non-probability sampling technique where participants are deliberately selected based on their specific knowledge, experience and characteristics relevant to the research objectives (Patton, 2002). This method allows researchers to identify and select information-rich cases that can provide deep insights into the central phenomenon being studied (Creswell & Poth, 2016).

Purposive sampling was appropriate for this study because integrating renewable electricity into SA's power system requires specialised knowledge across multiple domains including engineering, policy, economics and environmental science. By deliberately selecting participants with relevant expertise, the study gathers high-quality data from those most knowledgeable about the challenges and potential solutions in renewable energy integration (Babbie, 2020).

Snowball sampling complemented purposive sampling as a secondary recruitment strategy. This method involved asking initial participants to recommend others who meet the study criteria and might provide valuable insights (Hesse-Biber & Leavy, 2010). In the context of SA's energy sector, where professionals often work in interconnected networks, snowball sampling enabled access to experts who were otherwise difficult to identify or reach. This method is particularly valuable for accessing participants across different stakeholder groups, including government agencies, private sector companies, academic institutions and community organisations (Babbie, 2020).

Sample Size

The sample size for this study was determined by data saturation rather than pre-established numerical targets. Thus, data saturation refers to the point at which no new information or themes emerge from additional data collection (Fusch & Ness, 2015). This approach is particularly appropriate for qualitative studies exploring complex phenomena like renewable energy integration where the depth and quality of data are prioritised over quantity (Hennink et al., 2017). The study's initial target was 15 participants with the understanding that additional participants would be recruited until saturation was achieved.

In practice, data saturation was reached after conducting interviews with 11 participants representing diverse stakeholders across SA's energy sector. This sample size aligns with recommendations from methodological research suggesting that saturation in qualitative interviews with relatively homogeneous expert participants typically occurs between 11 and 20 interviews (Guest et al., 2006). The final determination of saturation was made when three consecutive interviews yielded no substantively new themes or insights beyond what had already been captured (Saunders et al., 2012).

The selection of participants was guided by carefully defined inclusion and exclusion criteria to ensure that participants had relevant expertise and could provide meaningful insights into renewable electricity integration in SA's power system. These criteria established clear boundaries for participation while ensuring the sample remained focused on individuals with pertinent knowledge and experience.

Inclusion Criteria

Each expert must meet these minimum requirements:

I. Direct operational experience in renewable electricity

II. generation and transmission systems

III. Current involvement in renewable integration

IV. Professional registration or equivalent

V. Demonstrated technical expertise through:

- Published technical papers.
- Project implementation experience
- Operational management roles

Exclusion Criteria

I. South African citizens not directly involved in the country's energy sector.
II. Individuals without relevant experience or knowledge of SA's electricity challenges.
III. Persons under the legal age of consent for research participation.
IV. Those unwilling or unable to provide informed consent.
V. People with no direct stake or involvement in SA's electricity landscape

3.5. The research instrument.

The primary research instrument employed in this study was a semi-structured interview guide. This guide serves as a flexible tool designed to facilitate in-depth discussions with key stakeholders in SA's energy sector (Creswell & Creswell, 2017). The semi structured interviews commenced with open-ended questions pertaining to the participants' roles and experiences within the energy sector, progressively transitioning to more specific inquiries regarding challenges, opportunities and potential solutions for renewable electricity integration. The guide encompassed prompts related to renewable energy potential, policy frameworks, socioeconomic impacts and environmental considerations. Importantly, it is not rigidly structured as it permits the interviewer to pursue intriguing lines of inquiry as they emerge. Moreover, the semi-structured nature of this instrument affords such flexibility (Leavy, 2014), ensuring that as the study's comprehension of the complex energy landscape in SA evolves, the research tools can be adapted to explore emerging themes more effectively.

3.6. Procedure for data collection

In the preparatory phase, the researcher sought ethical clearance from the Ethics Review Board (ERB) and obtained necessary permissions from relevant government departments and organisations (Creswell & Creswell, 2017). This step was crucial to ensure the research adhered to ethical standards and respects institutional protocols. Concurrently, the researcher developed research instruments, semi-structured interview guides.

To refine these instruments, a pilot study involved a small number of interviews conducted to allow necessary adjustments to the questions and protocols, enhancing their effectiveness for the main study (Yin, 2009). Following this, participant recruitment using purposive sampling to identify key informants was initiated, followed by snowball sampling to expand the participant pool (Patton, 2002). Interviews were then scheduled accordingly.

The data collection phase primarily involved semi-structured interviews. Prior to each interview, the interview guide was reviewed, and the recording equipment was prepared to ensure a suitable setting. During the interview, after obtaining informed consent, the researcher focused on building rapport with the interviewee while following the interview guide flexibly to explore emerging themes. With permission, the interview audio recorded, and notes were taken on key points and non-verbal cues (Bryman, 2016).

Post-interview, reflective notes were immediately be recorded, all data securely stored and preliminary analysis began to inform subsequent interviews. This iterative process continuously refined the data collection approach (Lungu & Marian, 2022).

3.7. Data analysis and interpretation

Thematic analysis (TA) was employed in this study. TA enabled the researcher to identify, analyse and report patterns within the data. The process involved 6 stages as guided by (Braun & Clarke, 2006):

1. Familiarisation with the data through transcription and repeated reading
2. Generating initial codes
3. Searching for themes
4. Reviewing themes

5. Defining and naming themes
6. Producing the report

The researcher employed qualitative data analysis software such as NVivo to assist in organising and analysing the large volume of textual data.

TA approach was selected because it offers a theoretically flexible method for identifying, analysing and reporting patterns within qualitative data making it particularly suitable for exploring the complex, multifaceted challenges of renewable electricity integration in SA. (Braun and Clarke's, 2006) systematic six-phase approach provides a robust framework that balances methodological rigour with interpretive flexibility.

The thematic analysis process followed these six phases as outlined by (Braun and Clarke, 2006; Braun and Clarke, 2019):

1. Familiarisation with the data - This initial phase involved immersion in the data through transcription of audio recordings from interviews, followed by repeated reading of the transcripts. During this process, preliminary notes were taken to mark potential patterns and meanings relevant to the research questions. As (King et al., 2018) emphasise, this phase is critical for developing the necessary intimacy with participants' accounts.

2. Generating initial codes - In this phase, systematic coding of interesting features across the entire dataset was conducted. Each segment of data relevant to the research questions was assigned descriptive codes. Both semantic codes (explicit content) and latent codes (underlying assumptions) were generated, following (Clarke & Braun, 2017) recommendation for a comprehensive coding approach. This resulted in approximately 60 initial codes before fine tuning.

3. Searching for themes - The codes were then organised into potential themes by identifying patterns and relationships. This phase involved moving from the micro level of codes to broader themes that captured important aspects of the data in relation to the research questions (Nowell, Norris, White & Moules, 2017).

Visual mapping techniques were used to explore relationships between codes and potential themes.

4. Reviewing themes - This crucial phase involved checking the themes against both the coded extracts and the entire dataset to ensure they accurately reflected the data. Following (Braun and Clarke's, 2006) guidance, this was conducted at two levels: reviewing coded data extracts to ensure coherence within themes and assessing the validity of individual themes in relation to the entire dataset. Some themes were refined, combined or separated during this iterative process.

5. Defining and naming themes - Each theme was then clearly defined and named to capture its essence and significance to the research questions. As Terry, Hayfield, (Clarke and Braun, 2017) suggest, this phase focused on identifying the "story" each theme tells and how it fits into the broader narrative of the study. Detailed descriptions were developed for each theme, including illustrative quotes.

6. Producing the report - The final phase involved the selection of compelling extract examples, relating the analysis back to the research questions and literature and producing a scholarly report of the analysis (Braun & Clarke, 2006). This process went beyond mere description to offer an interpretive analysis that contextualises the findings within the broader discourse on renewable electricity integration.

Throughout the analysis, a reflexive approach was maintained, acknowledging the active role of the researcher in identifying patterns and themes (Braun & Clarke, 2019). The analysis balanced inductive and deductive approaches - allowing themes to emerge from the data while also engaging with existing theoretical frameworks from the literature review.

To enhance the methodological rigour, several strategies were employed:

I. Regular peer debriefing sessions with colleagues familiar with the research area but not directly involved in the study.

II. Maintaining an audit trail documenting analytical decisions.
III. Member checking with selected participants to verify the interpretive accuracy.

NVivo 14 qualitative data analysis software was used to assist in organising and analysing the large volume of textual data. This facilitated more complex coding, theme development and data visualisation while maintaining the interpretive control of the researcher (Kekez, 2019). The software enabled efficient management of the data corpus while supporting the interpretive depth required for meaningful thematic analysis.

3.8. Trustworthiness and Credibility of the Study

In qualitative research, ensuring trustworthiness is crucial for establishing the rigour and value of the findings. This study addresses trustworthiness through four key components: credibility, transferability, dependability and confirmability (Lincoln & Guba, 1985).

3.8.1 Transferability

Transferability refers to the extent to which the findings can be applied to other contexts or settings (Korstjens & Moser, 2018).

While qualitative findings are context-specific, transferability was enhanced by:

I. Thick description - Detailed accounts of the research context, participants and methods were provided to allow readers to assess the applicability of findings to other settings (Saunder’s et al.,2012).
II. Purposive sampling - A diverse range of participants were selected to capture varied perspectives on sustainable energy supply in South Africa (Patton, 2007).

3.8.2 Credibility

Credibility refers to the confidence in the truth of the findings and is considered one of the most important factors in establishing trustworthiness (Lincoln & Guba, 1985).

I. Triangulation - Data was collected from multiple sources (interviews, document analysis) and compared to ensure consistency and comprehensiveness (Patton, 2018).
II. Member checking - Preliminary findings were shared with key participants to verify the accuracy of interpretations and conclusions (Creswell & Poth, 2018).
III. Prolonged engagement - Sufficient time was spent in the field to build trust with participants and gain a deep understanding of the context.
IV. Peer debriefing - Regular discussions with colleagues not involved in the study helped challenge assumptions and explore alternative interpretations (Lincoln & Guba, 1985).

3.8.3 Dependability

Dependability refers to the stability of findings over time and the extent to which the research process is documented in sufficient detail to allow for replication (Lincoln & Guba, 1985).

I. Audit trail - A comprehensive record of all research activities, decisions and reflections were maintained throughout the study (Lincoln & Guba, 1985).
II. Stepwise replication - The research process was clearly documented to allow potential replication by other researchers.

3.8.4 Confirmability

Confirmability refers to the degree to which the findings reflect the participants' perspectives rather than the researcher's biases or interests (Lincoln & Guba, 1985).

To establish confirmability and minimise researcher bias:

I. Reflexivity - A reflective journal was maintained to acknowledge and examine the researcher's biases, assumptions and influences on the research process (Creswell & Creswell,2017).
II. External audit - An independent researcher was invited to review the research process and findings to ensure they are supported by the data (Lincoln & Guba, 1985).

By rigorously addressing these four components of trustworthiness, this study aims to produce credible, context-rich findings that contribute meaningfully to understanding sustainable energy supply in SA.

3.9. Ethical considerations

Ethical considerations play a crucial role in shaping the approach and execution of this research on SA's energy landscape and transition. The study prioritised the well-being and rights of all participants throughout the research process.

First and foremost, informed consent was obtained from all participants before their involvement in the study. This process ensured that individuals were fully aware of the research objectives, potential risks and benefits and their rights as participants. Furthermore, clear, understandable information was provided, and participants were given ample opportunity to ask questions and voice any concerns before agreeing to participate.

Confidentiality and anonymity are paramount, particularly given the sensitive nature of renewable energy issues and their impact on communities (Leavy, 2017). Where required, strict measures were implemented to protect participants' identities. This included using pseudonyms, securing data storage and carefully handling potentially identifying information in the research outputs (Allen & Wiles, 2016).

To ensure the highest ethical standards were met, the research proposal was submitted to the institutional ethics review board for approval. This independent review assisted in identifying and addressing potential ethical issues before the study commenced. The researcher adhered to the guidelines and recommendations provided by the ethics board throughout the duration of the study.

RQ #	State Research Question	Prop #	State Proposition	Data collection detail	Data analysis method
1	What combination of utility- scale solar photovoltaic (PV), wind energy and grid- scale battery storage technologies can most effectively balance SA's decarbonisation objectives with grid reliability, leveraging the country's geographic distribution of solar and wind resources?	1	A diversified energy mix, hybrid systems (solar, wind, storage) maximize capacity factors and reduce reliance on single sources. Based on SA's geographic distribution of solar and wind resources, will enhance grid reliability while advancing the country's decarbonisation objectives.	Semi- interview questions	Thematic Analysis
2	How can phased integration of decentralised renewable energy systems (e.g., mini- grids, solar home systems) and modernisation of transmission infrastructure accelerate equitable electricity access and decarbonisation in South Africa's rural and peri-urban regions?	2	The phased integration of decentralised renewable energy systems coupled with modernisation of transmission infrastructure will significantly accelerate equitable electricity access and support SA's decarbonisation efforts in rural and peri-urban regions.	Semi interview questions	Thematic Analysis
3	What policy frameworks and localised initiatives (e.g., skills retraining, community- owned renewable projects) are critical to ensuring a just transition for coal-dependent communities such as Mpumalanga, while fostering economic diversification through renewable energy sectors?	3	Implementing targeted policy frameworks and localised initiatives, such as skills retraining programs and community-owned renewable projects will be essential for ensuring a just transition in coal-dependent communities such Mpumalanga while enabling economic diversification through the renewable energy sector.	Semi interview questions	Thematic analysis

Table 12 Consistency table: research questions, propositions, data collection and data analysis

4. FINDINGS & DISCUSSION (Qual)

4.1. Introduction

The researcher presents the findings and discussions in this chapter, starting with an overview of the key identified codes, themes and provides a detailed discussion of the findings under each theme. Finally, the researcher conducts a critical interpretive discussion under each theme.

4.2. Findings and discussions pertaining to Proposition 1

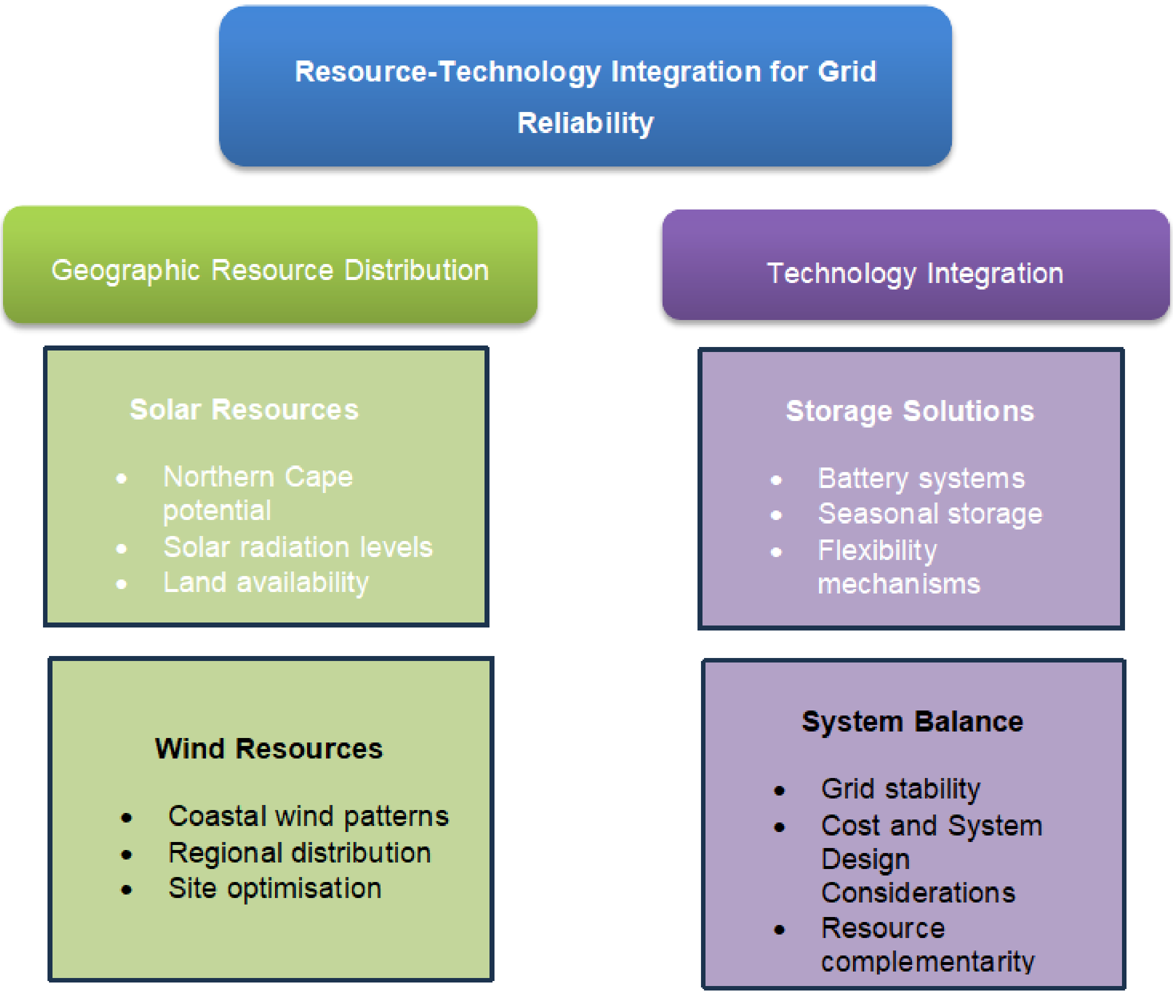

Figure 3 Resource-Technology Integration for Grid Reliability Theme

Key Integration Insights

• Geographic resource distribution drives technology deployment decisions

• Storage solutions critical for managing resource variability

• Balanced technology mix essential for system reliability

• Intermittency

The analysis of interview data revealed key insights about the combination of renewable energy technologies and their geographic distribution in SA's power system. Two major themes emerged from the data: Geographic Resource Distribution and Technology Integration Requirements. These themes provide important insights into how SA can effectively balance its decarbonisation objectives with grid reliability.

Theme 1: Geographic Resource Distribution

While SA's geographic advantages (e.g., solar in Northern Cape, wind on coasts) are well-documented in the IRP and public data, **participants revealed critical implementation gaps not adequately addressed in literature**

Regional Variation and Strategic Deployment

Participants revealed infrastructure mismatch (not just resource potential) dictate realistic deployment. Participant 1: "*You know that the Northern Cape and around the coast, that's where the good renewable energy sources are. But there is no infrastructure to support.*" This highlights a policy-implementation disconnect while the IRP identifies optimal zones, interviewees stress that transmission bottlenecks (e.g., lack of grid access in high-potential areas) undermine deployment. This supports but extends Mehta et al. (2023) by showing how infrastructure gaps in practice exacerbate the "energy paradox" (Daniel-Durandt et al., 2024).

Seasonal and Temporal Variations

The highlights the seasonal variability on operational realities expressed by Participant 7 *"In winter you don't have enough energy to produce full power."* This contributes to knowledge by Dalton et al. (2019) note seasonal fluctuations, participants prioritize their operational impact (e.g., winter shortages requiring backup systems), urging planners to move beyond theoretical potential.

These seasonal considerations extend existing literature by highlighting the operational challenges that theoretical resource assessments may not fully capture. While resource mapping studies identify potential generation capacity, our findings suggest that implementation planning must incorporate detailed seasonal modelling to ensure system reliability.

Complementary Resource Utilisation

The identification of complementary technologies localized Strategies as noted by Participant 5 "*Wind energy complements solar, as it often generates power during the night and cloudy days*". Interviews reveal community-level insights on hybrid systems (e.g., coastal towns leveraging wind-solar synergy), whereas Karamanski & Erfort (2023) focus on national-scale modeling.

Our findings extend this understanding by highlighting the potential for strategic geographic deployment of complementary technologies. Unlike previous studies that have examined technologies in isolation, participants emphasised an integrated approach that leverages the geographic distribution of different resources.

Infrastructure Constraints and Implementation Challenges

Perhaps most significantly, our findings reveal that theoretical resource potential cannot be separated from practical implementation constraints. The infrastructure limitations highlighted by participants represent a critical barrier that has not been sufficiently addressed in resource assessment studies. These supports (Mehta et al., 2023) recent work on multi-nodal energy systems modelling, which found that transmission bottlenecks limit renewable energy integration, emphasising the need for grid flexibility and strengthening.

The emphasis on infrastructure constraints extends Baker and Phillips, (2019) research on renewable energy sitting by providing a more nuanced understanding of implementation challenges. While Baker et al. focused primarily on identifying locations based on resource quality, our findings suggest that implementation planning must simultaneously address transmission infrastructure development to unlock these resources.

Theme 2: Technology Integration Requirements

The second major theme that emerged centred on the integration of various technologies to ensure system reliability. Participant 1's insights were particularly valuable emphasising that flexibility is non-negotiable "*You need to design your system to be flexible to be able to meet those changes and fluctuations."* This Challenges the IRP's static assumptions by emphasizing real-time adaptability needs. Furthermore, storage solutions emerged as a crucial component of successful integration. Participant 6 emphasised this point, stating "*You address that, or you mitigate that challenge by energy storage or flexibility in the system*." This analysis revealed a sophisticated understanding of various storage options with participants discussing multiple technologies.

The interview data showed strong support for a diversified technology approach. Participant 8 articulated this clearly, suggesting the combination of "*solar, wind, biomass and small-scale hydro with advanced storage technologies.*" This proposes context-specific mixes (e.g., biomass in agricultural regions), diverging from literature's generic "renewable portfolio" recommendations. Integration Challenges and Solutions

Participants identified several key challenges in integrating renewable technologies, particularly regarding infrastructure constraints. Participant 7 noted, "*The biggest challenge is the infrastructure, the transmission infrastructure... You need to design your system to be flexible, to be able to meet those changes and fluctuations*."

However, solutions were proposed, including diverse technology combinations, "*By combining solar, wind, biomass and small-scale hydro with advanced storage technologies, smart grids and green hydrogen, SA can meet its decarbonisation* *goals while maintaining system reliability*." Participant 10. These findings support (Gallegos, Arévalo, Montaleza, & Jurado's, 2024) work on sustainable electrification strategies while providing practical insights into implementation. Participant 6 mentioned, *"Without condensers, renewables will destabilize the grid."* This solution is overlooked tech-specific inertia solutions in literature**.**

Cost and System Design Considerations

Participant 3 highlighted storage solution cost realities versus reliability trade off," *We don't want to invest in all of these renewables which is clean, but you need so much gas and storage that at the end of the day, your system is becoming so expensive*." This exposes a policy blind spot participants question cost-effectiveness of over-reliance on storage, contrasting with Gallegos et al. (2024)'s optimistic tech assessments. Furthermore, Participant 4 mentioned hidden costs "*Batteries for utility-scale wind cost three times initial estimates*." CSIR (2021) estimated battery storage costs and applications in South Africa to be ZAR 5,000–7,000/kWh for utility-scale batteries. Gallegos et al. (2024) advocate storage, but participants warn of underestimated costs undermining feasibility. Principal-agent theory reveals the deeper structural tensions in Participant 11's cost concerns, "*We don't want to invest in all of these renewables, which is clean, but you need so much gas and storage that at the end of the day, your system is becoming so expensive*". This response exemplifies the classic principal-agent problem where government decarbonisation objectives (principal) systematically conflict with private sector risk assessment and return optimisation (agent). The participant's emphasis on total system cost rather than policy compliance suggests fundamental information asymmetries about how transition costs and risks are allocated between public and private actors, creating rational resistance to technically sound renewable deployment strategies. Participant 5 emphasized on **Strategic battery storage placement at transmission nodes "***Locating storage only at renewable plants not in townships means wealthy areas get grid stability while poor communities bear curtailment risks. This replicates apartheid-era infrastructure inequities.*" This further aligns with the energy justice theory, systemic inequity infrastructure planning, linking to historical spatial injustice.

Discussion and Implications

These findings suggest that successful renewable energy integration in SA requires:

I. Strategic Geographic Deployment - As emphasised by participants, renewable technologies must be deployed where resources are favourable. However, this must be balanced against infrastructure constraints.

II. Integrated Storage Solutions - The data strongly supports the need for storage technologies to manage variability, as articulated by participant 10: "*You address that, or you mitigate that challenge by energy storage or flexibility in the system*."

III. System Flexibility: The findings indicate that system design must priorities flexibility, supporting (Tran, et al., 2022) studies on managing the transition to high renewable penetration while maintaining grid stability.

IV. Technology Complementarity: The data suggests that combining different renewable technologies with appropriate storage solutions is crucial for system reliability. These findings both validate and extend existing research on renewable energy integration in developing economies. They particularly emphasise the practical challenges and solutions for implementing theoretical frameworks in the South African context contributing new insights to the field of renewable energy integration.

4.3. Findings and discussions pertaining to Proposition 2

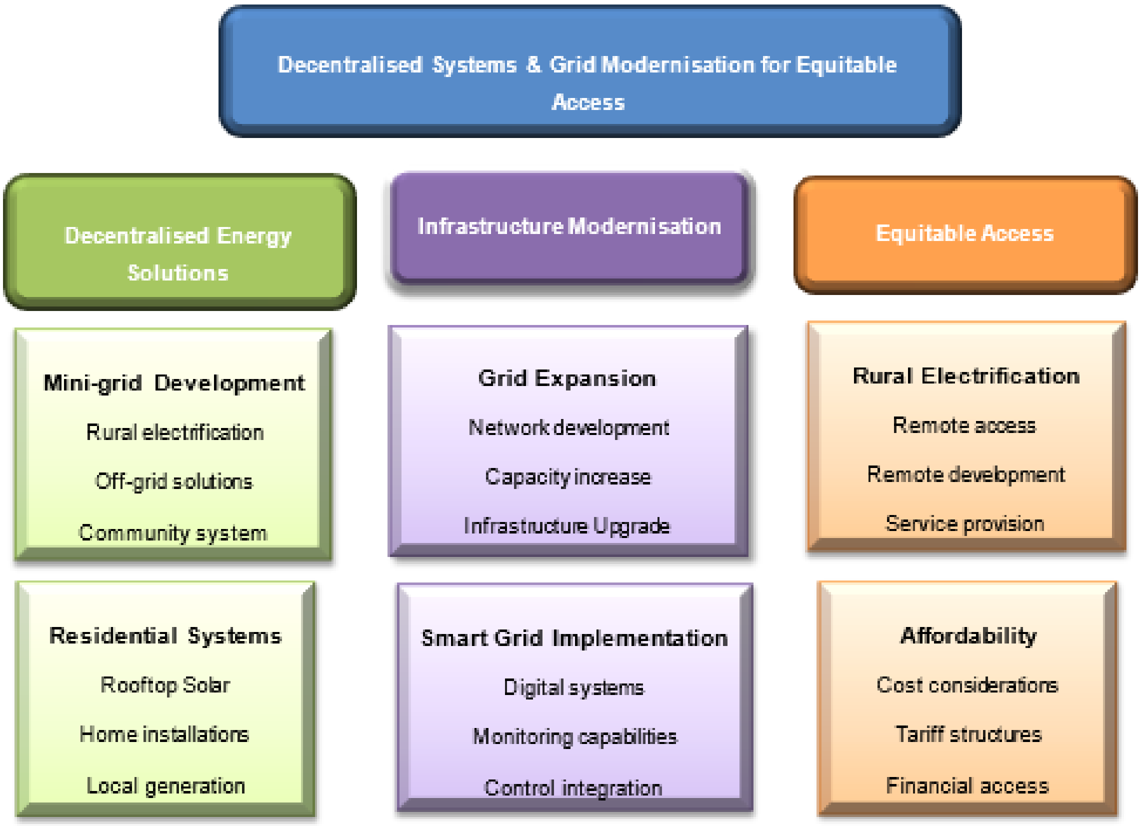

Figure 4 Decentralised Systems & Grid Modernisation for Equitable Access Theme

Key Integration Insights:

• Decentralised systems crucial for rural access

• Grid modernisation enables renewable integration

• Affordability key to equitable access

The analysis revealed three major themes regarding how decentralised renewable systems and modernised infrastructure can advance equitable electricity access in SA's rural and peri-urban regions. Each theme is supported existing literature by participant quotes and related to existing literature.

Decentralised Energy Systems and Just Transition Policies

The findings reveal decentralised energy systems as critical enablers of expanded electricity access in SA, particularly in underserved areas. Participant 7's observation that "*Microgrid projects in identified informal settlements can bring electricity to communities*" This demonstrates how decentralised systems can address immediate access challenges while creating economic opportunities through tiered licencing. This perspective extends (Sakah, Diawuo, Katzenbach & Gyamfi, 2017) work on sustainable electrification strategies by articulating specific implementation pathways that incorporate community participation and employment generation.

While decentralised systems offer clear benefits, some interview participants raised concerns about scalability and long-term sustainability. For instance, Participant 2 cautioned that *"without proper regulatory frameworks, microgrids may struggle with maintenance and equitable energy distribution."* These challenges the assumption that decentralisation alone guarantees success, aligning with Sovacool & Dworkin's (2015) critique of over-reliance on small-scale solutions without systemic policy support.

Additionally, while Fakoyede et al. (2024) highlight residential solar systems as key contributors to renewable energy, Participant 5 noted that *"low-income households often lack upfront capital for installations, raising equity concerns."* This introduces a critical counterpoint to the optimism around residential solutions, suggesting that financial mechanisms (e.g., subsidies, PAYG models) must accompany technological deployment. Participant 7 emphasized on Benefit-sharing models and touches on the theoretical lens of principal agent theory. "*Pilot microgrid projects in high-need areas like informal settlements coupled with skills training."* Integrating decentralised systems into national grids, leveraging lessons from early-stage projects ensures equity (Sakah et al., 2017; Fakoyede et al., 2024). A phased approach mitigates risks while aligning with just transition principles by prioritising inclusivity and adaptive learning.

Transmission Infrastructure Modernisation: Enabling Renewable Integration and addressing Policy and regulatory barriers

Infrastructure modernisation emerged as a foundational requirement for renewable energy expansion, with both physical and technological dimensions. Participant 11's specific recommendation to "*Expand SA's transmission network by over 14,000 km of new transmission lines and 170 substations*" provides concrete quantification of infrastructure needs that goes beyond general assessments found in existing literature. This detailed perspective on implementation requirements extends (Godinho, 2023) research on grid modernisation, which established the importance of transmission infrastructure but offered less specific deployment guidance.

The emphasis on smart grid capabilities represents an important advancement in understanding SA's infrastructure needs. Participant 11's reference to "*AI-powered grid control systems*" for real-time monitoring and demand management reflects an appreciation for advanced technological solutions that align with (Gurung, Ghimeray & Hassan 2012) research on renewable energy technologies for rural electrification.

The strategic prioritisation of transmission development between resource-rich regions and demand centres, exemplified by Participant 10's comment on constructing lines "*from the sunny Northern Cape's solar farms to Gauteng,"* addresses a critical planning dimension that receives insufficient attention in existing literature. This finding complements recent work by (Steenkamp, 2017) on policy options for clean electricity supply in SA, which identified transmission constraints as barriers but did not articulate specific geographic priorities for infrastructure development.

Interview data revealed systemic frustrations with bureaucratic delays in renewable energy approvals. Participant 6 stated "*The current permitting system is fragmented developers must navigate multiple agencies, causing years of delays.*" This aligns with literature on Bureaucratic Bottlenecks in Energy Projects (Eberhard & Naudé, 2017) but extends it by proposing a single-window clearance system "*We need one agency to consolidate environmental, grid, and land approvals which will significantly reduce CL and COD delays."* Similarly, standardised PPAs emerged as a critical need. Participant 9 noted "*Adjustment during CL and COD increases costs and uncertainty."* This finding contrasts with Katzenstein & Apt 2012 argues that regulatory inefficiencies increase soft costs in renewables, delaying COD. The establishment a unified digital or administrative as per global success cases the likes of Indias "PARIVESH" and “UDAY” portal, Dubai’s "DARI" system and Rwanda’s one-stop business registration serves as great lessons to ensure Single-Window Clearance System becomes a game-changer to South Africa’s Just Transition.

Equitable Access and Development: Balancing Technical and Socioeconomic Considerations

The findings demonstrate that equitable access requires attention to both technical solutions and socioeconomic conditions. Participant 8’s observation that “*Access to renewable energy at affordable tariffs will allow more communities to connect to electricity*” highlights the crucial link between affordability and accessibility that determines whether technical solutions translate into actual energy access. This perspective extends (Mirzania et al.'s 2023) research on energy justice by providing more granular insights into implementation challenges specific to the South African context.

The identification of cost barriers as significant concerns, exemplified by Participant 6’s mention of “*High upfront costs for renewable energy projects or systems and the affordability amongst the poor and the working class*” addresses an often-overlooked dimension of renewable energy transitions. This finding aligns with (Winkler’s, 2017) research on reducing energy poverty through carbon tax revenues in SA, which identified affordability as a key barrier to energy access. However, our participants offered more specific insights into how these economic barriers manifest in various community contexts.

The emphasis on reducing dependence on hazardous energy sources like paraffin connects renewable energy development with immediate health and safety concerns in vulnerable communities. This dimension of energy transition is often underrepresented in technical and policy discussions but emerges as a significant motivation for renewable adoption at the community level. This finding supports (Heffron and McCauley, 2017) conceptualisation of energy justice, which emphasis's the distributional, procedural and recognition elements of just energy transitions.

Synthesis and Theoretical Implications

Collectively, these findings contribute to a more integrated understanding of how decentralised systems, infrastructure modernisation and equity considers interaction in SA's energy transition. While existing literature often treats these dimensions separately, the findings reveal their interdependence and suggest that effective implementation requires attention to all three aspects simultaneously.

The emphasis on community engagement in decentralised energy deployment extends traditional technical approaches represented in (Gooding et.,. 2023) work on smart local energy systems. By highlighting participatory dimensions of implementation, this study's findings contribute to a more socially embedded understanding of energy transitions that aligns with recent developments in energy justice theory.

Similarly, the detailed perspectives on infrastructure modernisation requirements provide practical implementation insights that advance (Al-Shetwi et al., 2020) research on grid integration challenges. By identifying specific technological priorities and geographic considerations, our findings bridge the gap between technical analysis and implementation planning that often characterises the literature on grid modernisation.

The attention to affordability and accessibility as key dimensions of equitable energy access reinforces the importance of economic considerations in technical planning. This integrated perspective supports (Sovacool and Dworkin’s, 2015) energy justice framework by demonstrating how technical solutions must be implemented with attention to distributional outcomes to achieve equitable results.

In conclusion, these findings suggest that successful renewable energy integration in SA requires coordinated attention to decentralised systems, infrastructure modernisation, and equity considerations. This integrated approach extends beyond the predominantly technical or policy-focused literature to offer a more comprehensive framework for implementing sustainable and equitable energy transitions in the South African context.

4.4. Findings and discussion pertaining to Proposition 3

Figure 5 Just Transition for Coal-Dependent Communities

Key Integration Insights

• Economic transition requires comprehensive support

• Policy frameworks must address both individual and community needs

• Community empowerment essential for successful transition

Analysis of the interview data revealed three major themes regarding how policy frameworks and localised initiatives can support a just transition in coal-dependent communities. These themes provide insights into both challenges and potential solutions.

Theme 1: Economic Transition Challenges

The data revealed deep concerns about the economic impacts of transitioning away from coal, particularly in communities heavily dependent on the coal industry. This was evident in participants' direct experiences: Participant 9 "*We banking on the couple of years I made a decision two years ago. I jumped ship from Kriel cause I saw the way Eskom performing the state of the plants. I saw that we going to close in less than six years."* This personal account reflects the immediate reality of transition impacts, supporting (Tladi, Kambule & Modley, 2024) research on employment impacts in transitioning communities. The broader community impacts were emphasised by another participant 4, "*If you look at Hendrina or Kriel power station. You not going to have a job. And you know it's tough because all the little mining towns have been abandoned."* These findings align with (Nel, Marais & Mqotyana, 2023) research on transition waves in coal-dependent regions while providing specific South African context.

Theme 2: Policy and Support Mechanisms

The participants responses emphasised the critical role of policy frameworks and support mechanisms in managing transition impacts. Participants highlighted specific requirements, participant 1 "*Provide training programs to equip workers with skills for the renewable energy sector... Promote employment in related industries, such as manufacturing solar panels and wind turbines.*" This aligns with Malamatenios, (2016) work on employment and skills required in the renewable energy sector, and initiatives to address skill shortages. On the other hand, financial support mechanisms were identified as crucial, participant 3 "*Fund covers worker retraining, economic diversification and renewable energy investments and compensates utilities for early decommissioning of coal plants.*" These findings extend (Fakir, 2023) research on the Just Energy Transition Partnership insights into funding mechanisms for energy transition in SA.

Theme 3: Community Empowerment and Ownership

A key finding was the importance of community engagement and ownership in transition processes. Participants 8 emphasised active participation, "*Facilitate cooperatives where communities own and benefit directly from renewable energy projects... actively engaging stakeholders to identify and develop renewable electricity projects".* The need for comprehensive social protection was highlighted by participant 6, *"Implement social protection measures, such as unemployment benefits and job placement programs... ensure that renewable projects prioritise local hiring and procurement."* These findings support (Mirzania et al., 2023) research on energy justice while providing specific insights into implementation mechanisms.

4.5. Summary of the findings

The analysis of interview data revealed three key areas of insight regarding SA's energy transition: renewable energy integration, infrastructure development and just transition implementation.

For renewable energy integration, geographic resource distribution emerged as critical. The Northern Cape was identified as favourable for solar development, while coastal regions showed strong wind energy potential. However, participants emphasised that successful integration requires complementary technologies, particularly storage solutions. As participant 2 noted, "*You need to design your system to be flexible to be able to meet those changes and fluctuations.*"

Regarding infrastructure development, the findings highlighted the dual importance of decentralised systems and grid modernisation. Mini-grids and residential systems were identified as effective solutions for expanding energy access, particularly in rural areas. As noted by participant 4, "*Microgrid projects in identified informal settlements can bring electricity to communities*." Smart grid technologies and strategic network expansion were deemed essential for system reliability.

The just transition findings revealed significant challenges in coal-dependent communities. Participants 6 emphasised the need for comprehensive policy support, including skills development and financial assistance. Community empowerment emerged as crucial, with one participant 7 highlighting the importance of ensuring *“communities own and benefit directly from renewable energy projects*.”

4.6 Comparison of literature review and own findings

RQ	Research Question	Prop	Conclusion based on own research	Findings from own study
1	What combination of utility-scale solar PV, wind energy and grid-scale battery storage technologies can most effectively balance SA’s decarbonisation objectives with grid reliability, leveraging the country’s geographic distribution of solar and wind resources?	1	A diversified energy mix, hybrid systems (solar, wind, storage) maximize capacity factors and reduce reliance on single sources. Based on SA’s geographic distribution of solar and wind resources, will enhance grid reliability while advancing the country’s decarbonisation objectives.	The findings from Research Question 1 revealed that effective integration of renewable electricity in SA requires careful consideration of geographic resource distribution and technology combinations. Participants consistently emphasised that effective deployment of solar and wind resources depends heavily on regional characteristic.
2	How can phased integration of decentralised renewable energy systems (e.g., mini-grids, solar home systems) and modernisation of transmission infrastructure accelerate equitable electricity	2	The phased integration of decentralised renewable energy systems coupled with modernisation of transmission infrastructure will significantly accelerate equitable electricity access and support SA’s decarbonisation efforts in rural and peri-urban regions.	The findings from Research Question 2 demonstrated that successful integration of decentralised renewable energy systems requires a balanced approach to infrastructure modernisation and equitable access. Interview data revealed three critical

RQ	Research Question	Prop	Conclusion based on own research	Findings from own study
3	What policy frameworks and localised initiatives (e.g., skills retraining, community-owned renewable projects) are critical to ensuring a just transition for coal-dependent communities while fostering economic diversification through renewable energy sectors?	3	Implementing targeted policy frameworks and localised initiatives, such as skills retraining programs and community- owned renewable projects will be essential for ensuring a just transition in coal-dependent communities in Mpumalanga while enabling economic diversification through the renewable energy sector.	The findings from Research Question 3 revealed that implementing just transition in coal- dependent communities requires comprehensive policy support, economic diversification and active community participation. Interview data highlighted significant economic transition challenges, particularly in communities such as Mpumalanga where coal mining and power generation has been primary employers.

Table 13 Comparison of literature review and findings

5. CONCLUSIONS & RECOMMENDATION

5.1. Introduction

This study investigated the critical challenges and potential solutions for integrating renewable electricity into SA’s power system. Through in-depth interviews with energy sector stakeholders and comprehensive analysis of their perspectives, the research revealed complex interconnections between technical, economic and social dimensions of the energy transition. The findings provide important insights for policy makers and industry practitioners as SA works to balance decarbonisation objectives with system reliability and social equity.

5.2. Conclusions regarding research questions

For the second research question concerning decentralised systems and modernised infrastructure, the findings highlighted the critical importance of coordinated development approaches. Moreover, the research revealed that successful implementation of decentralised renewable systems requires careful attention to community capabilities and needs. While mini-grid projects proved most effective when communities participated in both planning and implementation, one participant specifically emphasised how this approach created valuable local employment opportunities.

The study also uncovered important insights about the relationship between grid modernisation and renewable integration. Thus, participants stressed that transmission infrastructure improvements must precede or accompany renewable deployment to prevent system instability. Hence, these finding challenges simplistic assumptions about the ease of renewable integration and highlights the need for carefully sequenced infrastructure development.

RQ #	State Research Question or Objective	State literature-based proposition or hypothesis	State conclusion or answer based on own research	Highlight key differences between your initial propositions / hypotheses and your findings – this is your contribution to knowledge
1	What combination of utility-scale solar photovoltaic (PV), wind energy, and grid-scale battery storage technologies can most effectively balance South Africa's decarbonisation objectives with grid reliability, leveraging the country's geographic distribution of solar and wind resources?	A diversified energy mix, hybrid systems (solar, wind, storage) maximize capacity factors and reduce reliance on single sources. Based on SA's geographic distribution of solar and wind resources, will enhance grid reliability while advancing the country's decarbonisation objectives.	The study's findings confirm the importance of a diversified energy mix but emphasise that effective configuration must be regionally specific. The Northern Cape's exceptional solar resources and the coastal regions' wind potential need to be connected through enhanced transmission capacity with storage strategically deployed at critical grid nodes. Participant interviews revealed that solar-wind complementarity varies significantly by location, requiring detailed regional modelling rather than broad national approaches	This study extends beyond the initial proposition by identifying specific geographic constraints and operational requirements. While the proposition focused on theoretical effectiveness, the findings reveal practical implementation challenges including: 1) The need for enhanced transmission corridors between renewable-rich regions and demand centres, 2) The importance of strategic battery placement at specific grid nodes rather than general deployment, and 3) The critical role of advanced forecasting systems integrated with battery management software for effective operation. These nuanced insights provide actionable guidance for system planners beyond general diversification principles

RQ	State Research Question or Objective	State literature-based proposition or hypothesis	State conclusion or answer based on own research	Highlight key differences between your initial propositions / hypotheses and your findings – this is your contribution to knowledge
2	How can phased integration of decentralised renewable energy systems (e.g., mini-grids, solar home systems) and modernisation of transmission infrastructure accelerate equitable electricity access and decarbonisation in South Africa's rural and peri-urban regions?	The phased integration of decentralised renewable energy systems coupled with modernisation of transmission infrastructure will significantly accelerate equitable electricity access and support SA's decarbonisation efforts in rural and peri-urban regions.	The study findings demonstrate that decentralised systems must be implemented with careful consideration of community needs and capabilities. Interviews with stakeholders revealed successful mini-grid implementations require robust local governance structures and maintenance capacity. Additionally, transmission modernisation needs to be coordinated with distributed generation to prevent grid instability. The most successful implementations occurred where communities had ownership stakes and participated in system design.	This study identifies a significant gap in the initial proposition - the critical importance of governance models and community participation. While the proposition focused primarily on technical integration, the findings reveal that: 1) Local ownership models significantly outperform externally managed systems, 2) Skills development must precede or accompany technical deployment, and 3) Regulatory frameworks need to explicitly address community-managed systems. These insights challenge the technology-first approach often taken in policy frameworks and emphasis institutional arrangements as equally important to technical solutions.

RQ	State Research Question or Objective	State literature-based proposition or hypothesis	State conclusion or answer based on own research	Highlight propositi this is yo
3	What policy frameworks and localised initiatives (e.g., skills retraining, community-owned renewable projects) are critical to ensuring a just transition for coal-dependent communities in Mpumalanga, while fostering economic diversification through renewable energy sectors?	Implementing targeted policy frameworks and localised initiatives, such as skills retraining programs and community-owned renewable projects, will be essential for ensuring a just transition in coal-dependent communities in Mpumalanga while enabling economic diversification through the renewable energy sector.	This study findings highlight that effective just transition frameworks must be multi- dimensional and contextually sensitive. Interviews with coal-dependent community members and energy sector workers revealed that successful transitions require sequential policy implementation rather than simultaneous interventions. Economic security must precede skills transition, which must then be followed by new industry development. Community- owned renewable projects showed promising results only when accompanied by comprehensive support systems including technical assistance, access to capital, and market connections.	This study just transi propositio findings re interventio economic Geograph and renew overlooke require su initial func transition with a mo implemen spatial dir approach

Table 14 Consistency table: research questions, conclusions and contribution to knowledge

5.3. Recommendations

Research on integrating renewable electricity into SA's power system reveals that a multifaceted strategy is essential to overcome technical, policy and social hurdles. This study recommends that SA focuses on its most abundant resources by developing utility-scale solar projects in the sun-drenched Northern Cape and wind farms along the coast, paired with grid-scale battery storage at strategic transmission nodes. Instead of a one-size-fits-all approach, regional modelling should guide where these systems are placed ensuring that different energy sources complement each other.

On the policy front, streamlining regulatory processes through a single-window clearance system and standardising power purchase agreements will reduce administrative delays and boost investor confidence. Clarified guidelines for grid access and energy wheeling are expected to encourage broader private sector participation.

Decentralised solutions are highlighted as well. The establishment of regulatory frameworks and technical guidelines for mini-grids and community energy systems together with tiered licensing based on system capacity can reduce entry barriers for small-scale projects and ensure safety and interoperability.

Community engagement emerges as a central theme. The research emphasises that formal consultation mechanisms from project inception through implementation and benefit-sharing models are vital for securing local support and sustainability. Providing technical assistance and capacity building for community energy cooperatives can further empower local stakeholders.

For coal-dependent regions, particularly in Mpumalanga, a carefully sequenced transition is necessary. Prioritising economic security measures before launching skills transition programs and aligning renewable development with former coal regions can maximise socio-economic benefits and smooth workforce transitions.

5.4. Suggestions for further research

The study on renewable electricity integration in SA's power system has enlightened several areas that warrant deeper investigation. As such, future studies should explore these knowledge gaps to further enhance understanding and implementation of sustainable energy solutions in the South African context.

The intersection of water constraints and energy system planning represents another critical research area. As SA faces increasing water scarcity (du Plessis & du Plessis, 2017), understanding the water-energy nexus implications of different renewable integration pathways could inform more sustainable planning decisions. This should include comparative water consumption analysis between conventional and renewable generation technologies across diverse geographic contexts.

This study suggests a phased implementation approach. As such, pilot projects with clear performance metrics should pave the way for scaling up successful models across diverse regions. Therefore, establishing a dedicated coordination body with representatives from government, industry, communities and academia will enhance stakeholder collaboration and ensure that renewable integration drives improvements in system reliability, environmental sustainability and socio-economic development.

The economic dimensions of energy storage deployment require more granular investigation. While this study identified the importance of battery storage for renewable integration, further research should examine the sizing, placement and economic models for different storage technologies across SA's diverse regions. This should include analysis of value stacking opportunities where storage systems provide multiple grid services simultaneously, potentially improving their economic viability.

Finally, cross-country comparative studies examining renewable integration experiences in other middle-income countries with similar constraints would provide valuable lessons for SA. Detailed analysis of successful integration approaches in countries with comparable economic structures, grid constraints and socioeconomic challenges could identify transferable lessons while accounting for SA's unique context.

These suggested research directions would build upon the foundation established in this study addressing critical knowledge gaps and providing more detailed guidance for SA's renewable electricity integration journey. By pursuing these research avenues, scholars and practitioners can contribute to more effective, equitable and sustainable energy transition pathways tailored to SA's specific needs and opportunities.

5.5 Limitations of the study

This study provides critical insights into the topic challenges and solutions for renewable electricity integration in South Africa's power system, but several limitations must be acknowledged:

i. **Methodological Limitations**

Due to the qualitative nature of this study, which aimed in providing rich, in-depth data limits statistical analysis of trends and the general feasibility of findings to the broader South African population or other contexts (Creswell & Poth, 2016). The study's insights are specific to the participants and contexts studied and caution should be exercised when extrapolating these findings as potential interviewer bias in interpreting stakeholder responses (though reflexivity was practiced).

Mitigation in future studies triangulation with policy documents, energy use datasets or making use of a qualitative approach combined with modelling or simulation, should be used to strengthen the analytical robustness needed for grid reliability and technical feasibility discussions institutional and expert backgrounds (e.g., policymakers, industry representatives). While this approach yielded in-depth perspectives, the small sample size limits the generalizability of findings.

Underrepresentation of grassroots voices of communities, end-users, and local advocacy groups was not included, which may skew results toward technocratic or top-down solutions, particularly for Research Questions 2 and 3.

To mitigate future studies should expand participation through purposive sampling of marginalized groups and mixed methods approaches (e.g., surveys, focus groups) to balance expert and community perspectives.

ii. **Geographical Constraints:**

The study focuses on specific regions within SA, which may not fully capture the diversity of energy-related issues across the country. Rural and remote areas may be under-represented due to logistical challenges in accessing these locations. Interviews were limited to due to challenges of time constrains in obtaining approval in conducting interviews with stakeholders.

Mitigation: A broader multi-site study could capture diverse contextual factors.

iii. **Time Constraints**

The study's cross-sectional nature provides a snapshot of the current situation but may not capture long-term trends or changes in the rapidly evolving energy sector (Saunders et al., 2012). A longitudinal study would offer more comprehensive insights into the dynamics of energy transition over time.

While these constraints necessitate caution in extrapolating results, they highlight opportunities for deeper investigation particularly in amplifying community voices and expanding methodological diversity. Addressing these gaps could yield more holistic policy recommendations.

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APPENDIX

APPENDIX A (The participant information sheet)

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Participant Information shee

University of the Witwatersrand, Johannesbu
E-mail: 2452645@students.wits.ac.
Private Bag 3, WITS 205

Dear Sir / Madam

My name is Nthabiseng Mabuza I am a Master's student in Energy Leadership at the University of the Witwatersrand, Johannesburg. My supervisor is Dr Ayanda Magida. I am conducting a research study about the solutions and challenges to achieving sustainable electricity supply in South Africa. The study title is Challenges and Solutions for Sustainable Electricity Supply in South Africa

I am inviting you to take part in answering a questionnaire and a possible follow-up interview influenced by the questionnaire. If you decide to take part, your participation in this research study will last about 10 for questionnaire 60 minutes. The interview will take place at via a Microsoft Teams meeting at a time agreed upon based on your availability.

With your permission, I would like to audio record the interview. This data will be stored in google drive for the research period and will be deleted after ten years. Only the researcher will have access to the data.

During the research activity, I will need to ask for some personal information about you, including your name & surname, the organisation you work for and your role and experiences in the energy sector.

The questionnaire and interview can be anonymous based on your consent. When I share the results of the research study, I will not include your name or anything else that could identify you if you wish to remain anonymous.

If you decide to take part in the research study, it should be because you want to volunteer. You do not have to take part. You can stop being in the study at any time. You do not have to answer any questions if you do not want to. You will not get any direct benefits if you choose to join the research study. You will not lose any services, benefits or rights you would normally have if you decide not to join. Taking part in the research study will cost you your data You will not be paid for being in this research study.

The risks for this research study is minimal, no more than what happens in everyday life. Should you feel uncomfortable during the interview, I will stop the interview and continue another time.

This research study will be written up as a research report and publication. The report will be available on the university library website. If you would like to receive a summary of this report, I will be happy to send it to you.

If you have any questions during or afterwards about this research study, feel free to contact me or my supervisor on the details listed below. If you have any concerns or complaints about the ethical procedures of this research study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0) 11 717 1408, email hrecnon-medical@wits.ac.za.

Yours sincerely

esearcher:

ls. Nthabiseng Mabuza
tudent in Energy leadership | Wits Business School
: 2452645@students.wits.ac.za

Supervisor:

Dr Ayanda Magida, PhD
Lecturer in Digital Business | Wits Business School
Programme Director: PDM in Digital Business
Chairperson: WBS Ethics and Plagiarism Committees
E: ayanda.magida@wits.ac.za
T: +27 11 717 3953
W: www.wbs.ac.za

APPENDIX B (Participant agreement form)

WITS
UNIVERSITY
Wits Business School

Consent form
University of the Witwatersrand,
Wits Business school
2452645@students.wits.ac.za
Private Bag 3, WITS 2050

Please circle the relevant options below

The research study was explained to me. I understand what this study is about.	YES	NO
I understand that I can volunteer to take part in the study	YES	NO
I agree that the interview may be audio recorded.	YES	NO
I agree that direct quotations from my interview may be used by the researcher in their research report.	YES	NO
I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report unless Interviewee gives permission)	YES	NO
I agree that other researchers may use the information I provide in my interview/ (depending on their own ethics clearance being obtained) but my name and any personal information will not be used or passed on.	YES	NO

....
Name & Surname of participant)

....
Signature

....
Date

APPENDIX C (Interview guide)

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

RESEARCH QUESTIONAIRE

Research title: Challenges and Solutions for Renewable Electricity Integration in South Africa's Power System

1.	What is the participants' roles and experiences within the energy sector?
	Role:
	Experience
2.	What challenges, opportunities, and potential solutions for sustainable energy supply have you experienced or identified?
	Challenges:
	Opportunities:
	Potential solutions for sustainable energy supply:
3.	What has guided you in encompassing prompts related to renewable energy potential, policy frameworks, socioeconomic impacts, and environmental considerations.
	Renewable energy potential:
	Policy frameworks:
	Socioeconomic impacts:
	Environmental considerations:

4.	What combination of renewable electricity sources and complementary technologies can most effectively support South Africa's decarbonization pathway while ensuring system reliability, considering the country's geographical and climatic conditions?
5.	How can South Africa accelerate decarbonization through the strategic integration of renewable electricity sources while expanding access to reliable electricity supply?
6.	How can South Africa implement a just transition in coal-dependent communities through the creation of new opportunities in renewable electricity and complementary sectors?

APPENDIX D (Ethics approval)

Graduate School of Business Administration
University of the Witwatersrand, Johannesburg

Wits Business School

Wits Business School Ethics Committee
Constituted under the University Human Research Ethics Committee (Non-Medical)

Ethics Clearance Certificate

Ethics protocol number: WBS/EL2452645/993

This certificate is only valid with a legitimate ethics protocol number and signed by the Researcher (below).

This certificate is only valid if accompanied by formal permission from the relevant stakeholder(s).

Project title	Challenges and solutions for sustainable energy supply in South Africa
Investigator / Researcher	Ms Nthabiseng Mabuza
Nature of Project	MM (Energy Leadership)
Decision of the Committee	Approved, provided stakeholders and participants are guaranteed confidentialty.
Issue Date of Certificate	20/11/2024
Expiry date	Date of submission of the project / research report
Chairperson	Dr Ayanda Magida ☎ +27 11 717 3953 ayanda.magida@wits.ac.za

Declaration by Researcher

One copy must be signed by the Researcher and returned to the Chairperson of the Wits Business School Ethics Committee.

I fully understand the conditions under which I am authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I undertake to resubmit the protocol to the Committee.

Signature

21 November, 2024
Date: