processes

MDPI

Article

Evaluating the Role of Hybrid Renewable Energy Systems in Supporting South Africa's Energy Transition

Mxolisi Miller †, Xolani Yokwana *,† and Mbuyu Sumbwanyambe †

Department of Electrical and Smart Systems Engineering, University of South Africa, Johannesburg 1709, South Africa; 35483040@mylife.unisa.ac.za (M.M.); sumbwm@unisa.ac.za (M.S.)
* Correspondence: yokwaxp@unisa.ac.za
† These authors contributed equally to this work.

Abstract

This report evaluates the role of Hybrid Renewable Energy Systems (HRESs) in supporting South Africa's energy transition amidst persistent power shortages, coal dependency, and growing decarbonisation imperatives. Drawing on national policy frameworks including the Integrated Resource Plan (IRP 2019), the Just Energy Transition (JET) strategy, and Net Zero 2050 targets, this study analyses five major HRES configurations: PV–Battery, PV–Diesel–Battery, PV–Wind–Battery, PV–Hydrogen, and Multi-Source EMS. Through technical modelling, lifecycle cost estimation, and trade-off analysis, the report demonstrates how hybrid systems can decentralise energy supply, improve grid resilience, and align with socio-economic development goals. Geographic application, cost-performance metrics, and policy alignment are assessed to inform region-specific deployment strategies. Despite enabling technologies and proven field performance, the scale-up of HRESs is constrained by financial, regulatory, and institutional barriers. The report concludes with targeted policy recommendations to support inclusive and regionally adaptive HRES investment in South Africa.

Keywords: hybrid renewable energy systems (HRESs); integrated resource plan (IRP); just energy transition (JET); independent power producer (IPP)

check for updates

Academic Editors: Bonginkosi A. Thango, Katleho Moloi and Agha F. Nnachi

Received: 5 June 2025
Revised: 6 July 2025
Accepted: 16 July 2025
Published: 27 October 2025

Citation: Miller, M.; Yokwana, X.; Sumbwanyambe, M. Evaluating the Role of Hybrid Renewable Energy Systems in Supporting South Africa's Energy Transition. *Processes* **2025**, *13*, 3455. https://doi.org/10.3390/pr13113455

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction and Background

1.1. Global Energy Context

The global energy landscape is undergoing a profound transformation driven by the dual imperatives of climate change mitigation and energy security. The escalating reliance on fossil fuels throughout the 20th century has led to a significant increase in greenhouse gas emissions, contributing to global warming and environmental degradation [1–3]. In response, countries around the world are accelerating the shift toward decarbonised energy systems, integrating renewable energy technologies such as solar, wind, hydro, and energy storage into their national grids [4,5].

According to the UNEP Emissions Gap Report (2023), current national commitments place the planet on track for a temperature rise of 2.5 °C to 2.9 °C by 2100, far above the 1.5 °C limit agreed upon in the Paris Agreement [6]. The World Meteorological Organization (WMO) has confirmed that 2023 was the hottest year on record, with global temperatures reaching 1.45 °C above pre-industrial levels [7]. Despite these warnings, fossil fuel subsidies remain pervasive, and global emissions continue to rise, pointing to a critical implementation gap between pledges and action [8].

Consequently, Hybrid Renewable Energy Systems (HRESs) are receiving increasing attention globally as solutions capable of delivering reliable, clean, and flexible power, particularly in contexts that require both grid-connected and decentralised energy models [9,10]. The role of energy efficiency and system integration is equally critical in achieving energy transition targets by 2050, as underscored in recent IRENA and WEF analyses [11,12].

Africa is richly endowed with renewable resources, yet over 600 million people remain without electricity access, particularly in sub-Saharan regions [13]. This persistent energy poverty is rooted in weak infrastructure, underfunded utilities, and centralised fossil fuel dependency [14,15]. Many national utilities face operational and financial constraints, impeding rural electrification efforts [16].

However, momentum is growing around decentralised and Hybrid Renewable Energy Systems (HRESs) as viable solutions for expanding access. In Nigeria, Kenya, and Ethiopia, solar PV combined with batteries or diesel backup is increasingly deployed to power health clinics, schools, and mini-grids [17,18]. These hybrid systems lower costs and emissions while improving reliability, even under grid-deficient conditions [19].

Continental initiatives like the Africa Renewable Energy Initiative (AREI) and Agenda 2063 underscore the strategic role of renewables and HRESs in supporting inclusive, low-carbon development [20]. Yet, as [21,22] argue, successful implementation requires not just technology, but reforms in governance, financing models, and meaningful community engagement to ensure equitable energy transitions [23].

According to the Centre for Renewable and Sustainable Energy Studies (CRSES) [24], South Africa's total electricity demand has declined over the past decade, despite relatively stable peak levels (see Figure 1). From a peak of around 245 TWh in the early 2010s, annual system demand fell to below 210 TWh by 2024, reflecting both economic stagnation and growing grid unreliability. This decline underscores the urgency for diversifying generation and modernising the grid [24].

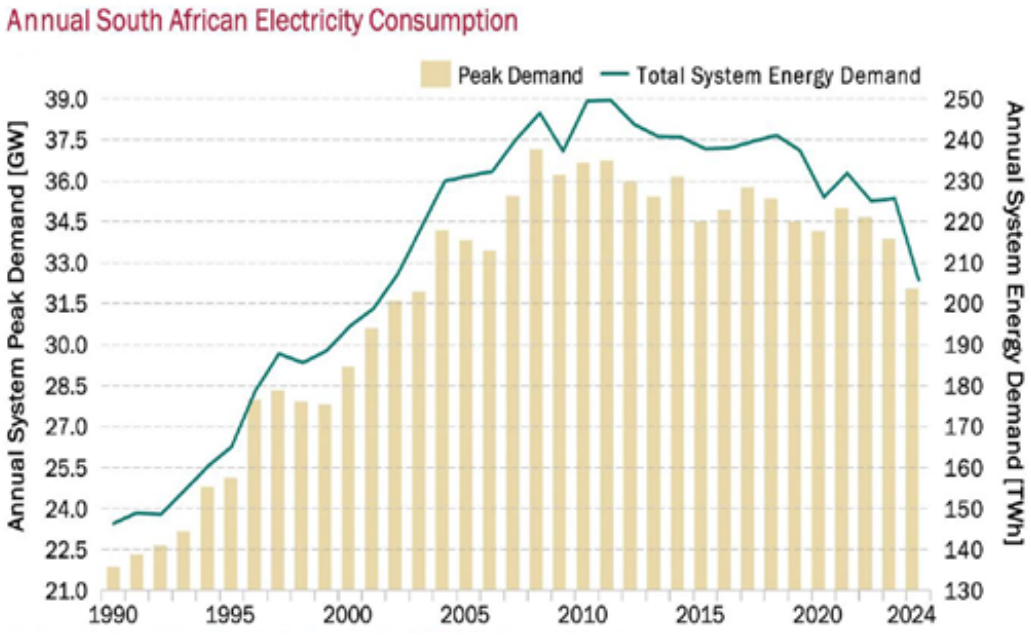


Figure 1. Annual South African electricity consumption: peak demand vs. energy use (Source: Centre for Renewable and Sustainable Energy Studies (CRSES) Stellenbosch University, 2025 [Online] [24]. Available: https://www.crses.sun.ac.za (15 May 2025)).

Furthermore, South Africa's electricity sector is heavily coal-dependent, generating over 80% of its power from coal-fired plants [25]. The system is marked by aging infrastructure, frequent breakdowns, and increasing load shedding, which in 2023, occurred on more

than 200 days [7,26]. These operational failures are symptomatic of deeper structural issues, including underinvestment, regulatory misalignment, and a fossil fuel-centric political economy [27].

As shown in Figure 2, the dominance of coal is visually reflected in 2024 projections, where coal comprises 72% of installed dispatchable capacity (39 GW) and 81% of electricity production (178 TWh), according to the Centre for Renewable and Sustainable Energy Studies (CRSES) [24]. Most large-scale coal plants are in the country's north and north-east, where Carboniferous and Permian coal seams are concentrated. Other dispatchable technologies, such as pumped storage, hydro, nuclear, and gas, exist but make up a significantly smaller share of generation. Non-dispatchable sources like solar PV and wind, while growing, remain underutilised in the national mix due to policy delays and grid constraints [28]. To address these converging crises, South Africa's Integrated Resource Plan (IRP) 2019 proposes a fundamental restructuring of the power system. It targets the decommissioning of over 10 GW of coal, and the addition of 6 GW of solar PV, 14.4 GW of wind, and 2 GW of battery storage by 2030 [12]. The Just Energy Transition (JET) framework supports this transformation by addressing socio-economic risks, especially for the coal-reliant Mpumalanga province, which faces the potential loss of more than 120,000 jobs [13,29].

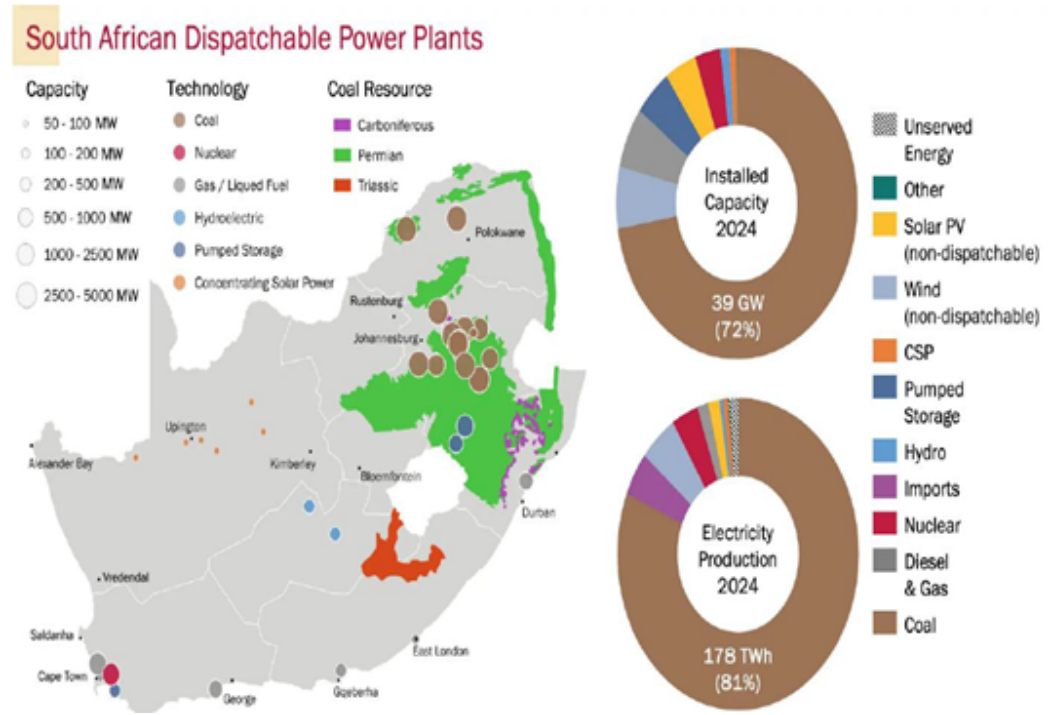


Figure 2. South African dispatchable power plants by technology and location (Source: Centre for Renewable and Sustainable Energy Studies (CRSES), Stellenbosch University, 2025 [Online] [5], Available: https://www.crses.sun.ac.za (15 May 2025)).

As shown in Figure 3, South Africa has already procured a total of 6.1 GW of non-dispatchable renewable energy under the REIPPPP programme by 2024, comprising 3.4 GW of wind and 2.3 GW of solar PV. These Independent Power Producer (IPP) installations are widely distributed, with strong spatial alignment to existing and planned grid infrastructure, particularly in the Northern, Eastern, and Western Cape regions. However, integration into the national system remains constrained by grid congestion and insufficient substation capacity. While positive progress has been made in South Africa, there, however, remains underutilisation of the abundance of solar and wind resources. South Africa continues to underutilise these resources due to policy delays, grid bottlenecks,

and institutional inertia [28]. In this context, Hybrid Renewable Energy Systems (HRESs) are increasingly recognised for their ability to decentralise supply, improve reliability, and enable low-emissions development [10,17]. These systems represent a technically feasible and socially responsive pathway toward a more just and sustainable electricity sector [22].

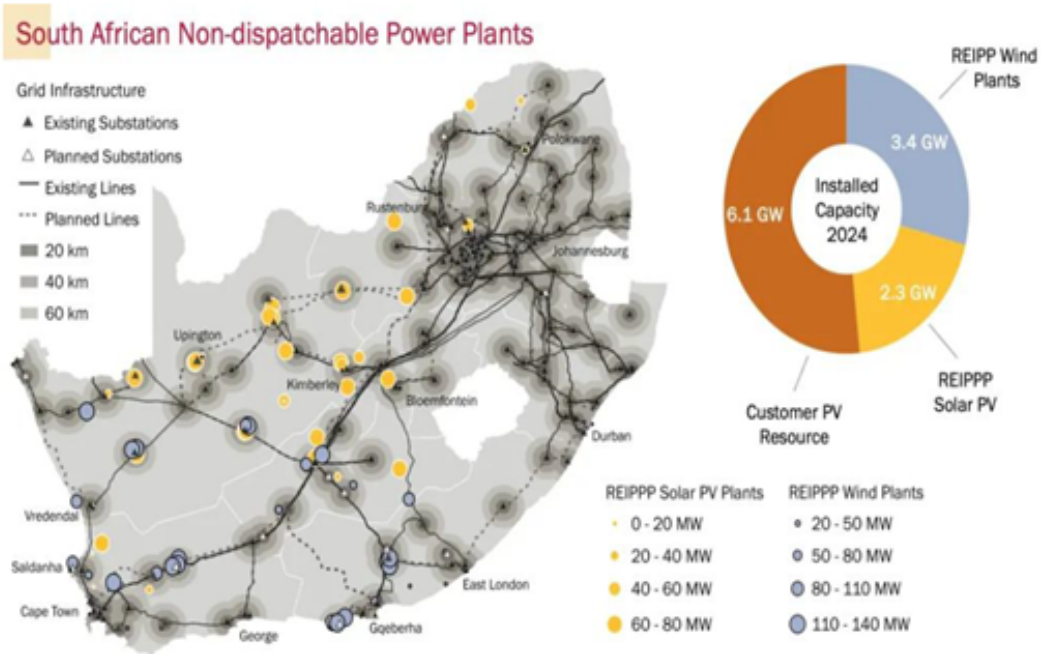


Figure 3. South African non-dispatchable power plants and grid infrastructure. Centre for Renewable and Sustainable Energy Studies (CRSES) Stellenbosch University, 2025 [Online] [24]. Available: https://www.crses.sun.ac.za (17 May 2025)).

Taken together, these global, regional, and national trends suggest that the transition to HRES in South Africa requires more than technological deployment. It demands structural change across institutions, regulatory frameworks, and planning paradigms. To understand how such policy transitions unfold, the next section explores the literature and policy gap towards transitioning to HRESs in South Africa.

1.2. Framing the Literature and Policy Gap in the Transition Towards HRESs

While HRESs are increasingly recognised as technically and economically viable in addressing South Africa's energy access and reliability challenges [10,13], their integration into national energy planning and infrastructure remains limited. This study identifies two interrelated but distinct gaps constraining the advancement of HRESs: a literature gap and a policy gap.

1.2.1. The Literature Gap

Academic research on HRESs in South Africa has primarily focused on techno-economic modelling, system optimisation, and hardware integration [11,12,30]. However, the socio-technical, institutional, and governance dimensions of the transition remain underexplored. Limited use has been made of frameworks such as the Multi-Level Perspective (MLP), which can help explain how innovations like HRESs interact with entrenched regime structures and broader exogenous pressures [2,31,32]. Few studies have systematically analysed the enabling policy and institutional conditions necessary for decentralised energy technologies to scale in the South African context [33,34].

1.2.2. The Policy Gap

Although national policy frameworks such as the Integrated Resource Plan (IRP 2019) [12] and the Just Energy Transition (JET) framework [29] acknowledge the importance of renewable energy, they fall short in providing clear, consistent, and decentralisation-enabling mechanisms for HRESs. Existing licensing frameworks, procurement protocols, and grid integration strategies remain aligned to centralised, utility-scale infrastructure [14,22,26]. In the context of HRES deployment, insufficient alignment of institutional responsibilities across Eskom, NERSA, municipalities, and national departments has contributed to policy gaps, coordination difficulties, and inconsistent implementation capacity [15,27]. Policy clarity also remains limited, particularly regarding licensing procedures, intergovernmental roles, and accountability mechanisms required to support decentralised and hybrid energy systems [35,36]. Recent implementation assessments and policy reviews underscore these challenges, citing institutional fragmentation, inconsistent mandates, and slow reform uptake as key obstacles [33,36].

This study responds to both gaps. By applying the MLP framework to the South African HRES context, it contributes to the academic literature through a socio-technical interpretation of the policy transition process. At the same time, it offers applied insights into the regulatory and institutional shifts required to support inclusive, decentralised energy systems as part of South Africa's broader energy transition.

1.3. Research Problem and Question

South Africa's energy system is undergoing a slow and uneven transition from a centralised, fossil fuel-dependent regime towards a more decentralised, flexible, and low carbon future. Hybrid Renewable Energy Systems (HRESs) offer promising technical solutions, especially in the context of unreliable grid supply and the urgent need for distributed generation. However, their adoption remains constrained by institutional fragmentation, regulatory inertia, and governance challenges, particularly at the municipal level. While recent policy reforms signal a shift, the structural dynamics underlying South Africa's energy transition remain poorly understood.

This study applies the Multi-Level Perspective (MLP) to analyse how these systemic factors shape the country's policy transition toward HRESs. The MLP framework conceptualises socio-technical transitions as emerging from interactions across three levels: niche-level innovations, regime-level institutions and practices, and broader landscape-level pressures. This framework enables a structured analysis of how policy, institutional, and governance dynamics interact across levels to either facilitate or hinder transition.

Research Question

How is the policy transition towards Hybrid Renewable Energy Systems in South Africa shaped by institutional, regulatory, and governance dynamics across the levels of the Multi-Level Perspective?

To address the research problem and guide the investigation, this study pursues the following objectives:

- To assess the technical and economic feasibility of selected HRES configurations, specifically PV–Battery, PV–Diesel–Battery, and PV–Biomass–Battery, using Levelised Cost of Electricity (LCOE) modelling.
- To analyse the policy, institutional, and regulatory barriers that affect the adoption and scaling of HRESs in South Africa, with particular attention to licensing procedures, procurement frameworks, and governance coordination.

- To apply the MLP as an analytical framework to interpret how niche innovations such as HRES, regime-level constraints, and broader landscape pressures interact in shaping South Africa's energy transition.
- To identify enabling conditions and policy recommendations that can support a more structured, inclusive, and decentralised transition to HRESs as part of the country's broader Just Energy Transition agenda.

1.4. Analytical Framework: The Multi-Level Perspective

The MLP on socio-technical transitions, introduced in [32], provides a widely accepted framework for analysing how complex energy systems evolve and undergo transformation over time [5,8]. It suggests that transitions unfold through long-term interactions among actors, institutions, and technologies operating across three interconnected levels: (a) the niche level, where radical innovations are incubated; (b) the socio-technical regime level, which maintains dominant systems; and (c) the landscape level, comprising broader exogenous pressures like climate change or macroeconomic trends [32]. By examining how these levels interact over time, the MLP helps explain the co-evolution of innovations and resistance within complex systems. These levels and their interactions are illustrated in Figure 4. This study applies the MLP framework to conceptualise South Africa's energy transition as a dynamic socio-technical process shaped by interactions across these levels:

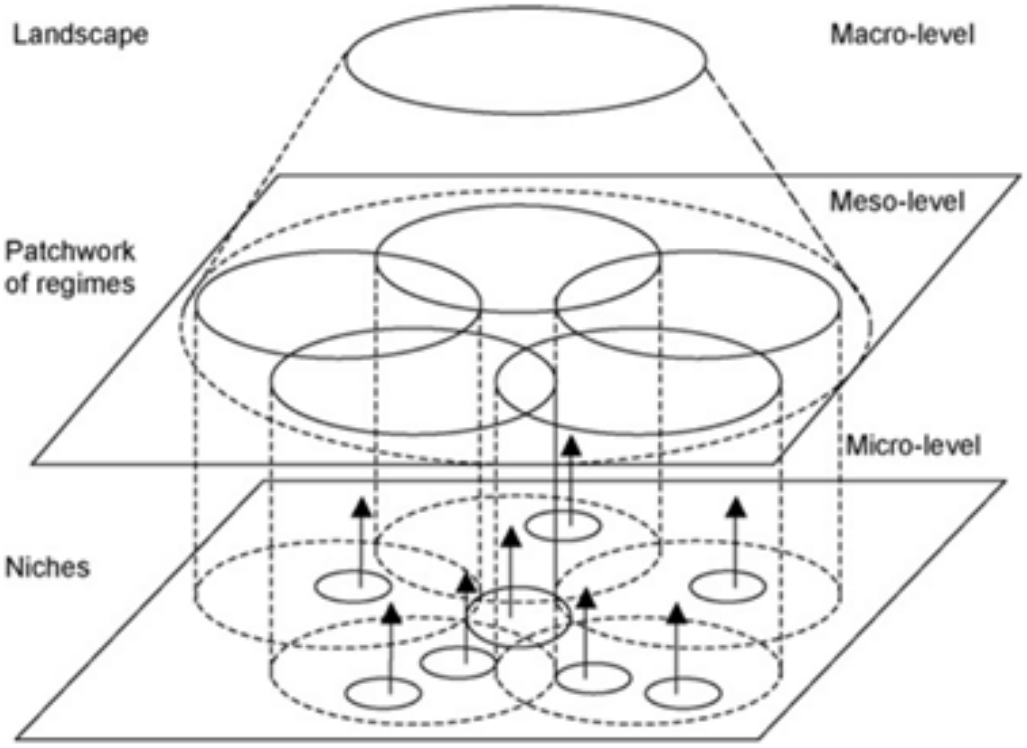


Figure 4. Multi-level framework for the analysis of socio-technical transitions [37].

- Landscape level: Refers to exogenous pressures and structural trends, such as global decarbonisation commitments, growing renewable investment, national energy insecurity, and the JET, that place strain on the existing system [14].
- Regime level: Encompasses dominant institutions, policies, and infrastructures that stabilise the current energy system. These include Eskom, the Department of Mineral Resources and Energy (DMRE), the Integrated Resource Plan (IRP), and the National Energy Regulator of South Africa (NERSA). Regime actors reinforce path dependency

and resist disruptive innovation through regulatory inertia, misaligned incentives, and policy uncertainty [8,14].

- Niche level: Protected spaces for innovation. In this study, Hybrid Renewable Energy Systems (HRESs), comprising solar PV, wind, storage, and backup diesel, are examined as niche technologies. While technically viable, they remain marginal within mainstream energy planning [10,38].

Despite its strengths, the MLP has been criticised for underplaying power dynamics, strategic agency, and political resistance [3–5]. It often treats regimes as monolithic and stable, overlooking internal contestation, elite interests, lobbying behaviour, and institutional lock-in mechanisms [15], issues especially relevant in South Africa's centralised energy sector.

In response, several studies have adapted the MLP to better account for politics and agency [6,15,16]. However, most of these applications remain concentrated in industrialised settings [5,7], with limited empirical work on decentralised transitions in developing countries [8,10,38] or citizen-led systems common in sub-Saharan Africa [11–14]. By analysing HRESs within South Africa's regime, this paper expands the MLP's empirical relevance and illustrates how institutional resistance can inhibit the adoption of viable decentralised energy innovations.

The MLP also informs this study's research design. This study analyses PV–Battery, PV–Diesel–Battery, and PV–Biomass–Battery systems as niche-level innovations. It combines techno-economic modelling with policy and institutional analysis to assess viability and understand barriers to scaling decentralised solutions.

2. Literature Review and Technology Overview

2.1. Theoretical Framing

This study adopts the Multi-Level Perspective (MLP) to interpret how Hybrid Renewable Energy Systems (HRESs) contribute to South Africa's energy transition. The MLP explains transition as the result of interactions across three levels: niche innovations, socio-technical regimes, and the broader landscape environment [1,32].

HRESs function as niche innovations, often emerging in protected spaces such as municipal microgrids or rural electrification pilots. These projects are typically supported by targeted policies, international financing, and local experimentation, allowing new actors to trial decentralised, low-carbon solutions outside the dominant energy system [3,32].

The incumbent regime, anchored by Eskom and coal-based generation, is characterised by institutional lock-in and resistance to change. However, persistent inefficiencies, including load-shedding and escalating costs, are exposing cracks in this dominant structure [31,32].

At the same time, landscape pressures such as climate imperatives, global energy trends, and domestic energy insecurity are reshaping the conditions under which regimes and niches interact. If aligned effectively, niche-level HRESs could scale and contribute to a more just and sustainable energy system [1,3,20,32,39].

The next subsections apply this framing to the South African context. Section 2.2 outlines the country's renewable energy resource base, Section 2.3 examines typical HRES system configurations, and Section 2.4 explores the institutional and economic drivers that influence their adoption.

2.2. Hybrid System Architecture, Technologies, and Applications

The system architecture and technologies underpinning HRESs function as niche-level innovations under the MLP framework, developed and refined through pilot projects that enable technical experimentation and learning [3,31]. Their uptake is influenced by

regime-level constraints like Eskom's grid codes and procurement rules, although advances in storage and control systems are improving integration [10,20]. Landscape dynamics, including falling technology costs and growing climate pressure, are accelerating adoption [39].

HRESs combine multiple energy generation and storage components such as PV, wind, diesel generators, lithium-ion batteries, and in some cases biomass or hydrogen to optimise reliability, reduce costs, and minimise environmental impact [7,8,18,40]. These systems are managed through centralised or decentralised Energy Management Systems (EMSs), which control power flow, load dispatch, and storage charging cycles [5,23,41].

System configurations vary by context. PV–Battery systems dominate institutional and residential microgrids, especially where reliability is essential, such as in clinics and schools [25,28]. PV–Diesel–Battery hybrids are often deployed in off-grid villages or load-shedding-prone areas where diesel serves as backup [20,42]. PV–Wind–Battery systems are more typical in coastal and industrial zones, offering complementary daily and seasonal generation profiles [8,43].

Advanced EMS platforms integrate AI-driven control, using real-time data to predict load patterns and optimise dispatch [5,23,44]. Studies from [7,8] demonstrate that optimally sized PV–Battery–Diesel hybrids in Limpopo can deliver Levelised Costs of Electricity (LCOEs) between USD 0.11 and USD 0.18 per kWh, outperforming diesel-only systems both economically and in emissions intensity. Lithium-ion storage technologies, while capital-intensive, deliver round-trip efficiencies above 90% and support frequency and voltage stability through inverter-based control mechanisms [45,46].

The integration of hybrid systems with the national grid requires compliance with inverter synchronisation standards, reactive power control, and grid code alignment [15,25]. Simulink and HOMER Pro remain the most widely used tools for techno-economic simulation and load-flow optimisation in South African case studies [46].

2.3. Contribution of HRESs to Grid Reliability and Load Management

South Africa's power system has been plagued by worsening grid instability, with load shedding occurring on over 200 days in 2023 [2,11,47]. HRESs offer an immediate and scalable solution to grid vulnerability. At the micro-level, they enable embedded generation that bypasses unreliable grid infrastructure [14,48]. At the meso-level, hybrid mini-grids reduce load on Eskom's centralised system by supplying resilient, localised power to communities and commercial users [22,49]. At the macro-level, hybrid industrial systems reduce the peak demand profile and provide predictable baseload contributions in renewable-dominant environments [16,25].

In Northern Cape mining operations, PV–Wind–Battery hybrids have reduced grid dependency by more than 40%, while maintaining stable power quality critical to mechanised operations [19,31]. EMS-coordinated Battery Energy Storage Systems (BESSs) support frequency regulation and black-start capability, making them vital for critical infrastructure resilience [5,23]. Moreover, HRESs reduce curtailment of intermittent sources by enabling time-shifting of energy through storage integration, thus smoothing the duck curve observed in PV-dense regions [50,51]. See Figure 5 for an example of a duck curve.

2.4. Role of HRESs in Advancing Policy Goals: IRP, JET, and Net Zero

The Integrated Resource Plan (IRP 2019) outlines an ambitious target of 22.4 GW of new renewable capacity by 2030, with goals including 6 GW of solar PV, 14.4 GW of wind, and 2 GW of battery storage [12,29,52]. However, grid bottlenecks, procurement delays, and the entrenched dominance of Eskom have slowed deployment [4,14,25]. HRES offer a

flexible and pragmatic bridge to accelerate renewable integration in constrained regions where large-scale utility projects face infrastructural and policy delays [27,46].

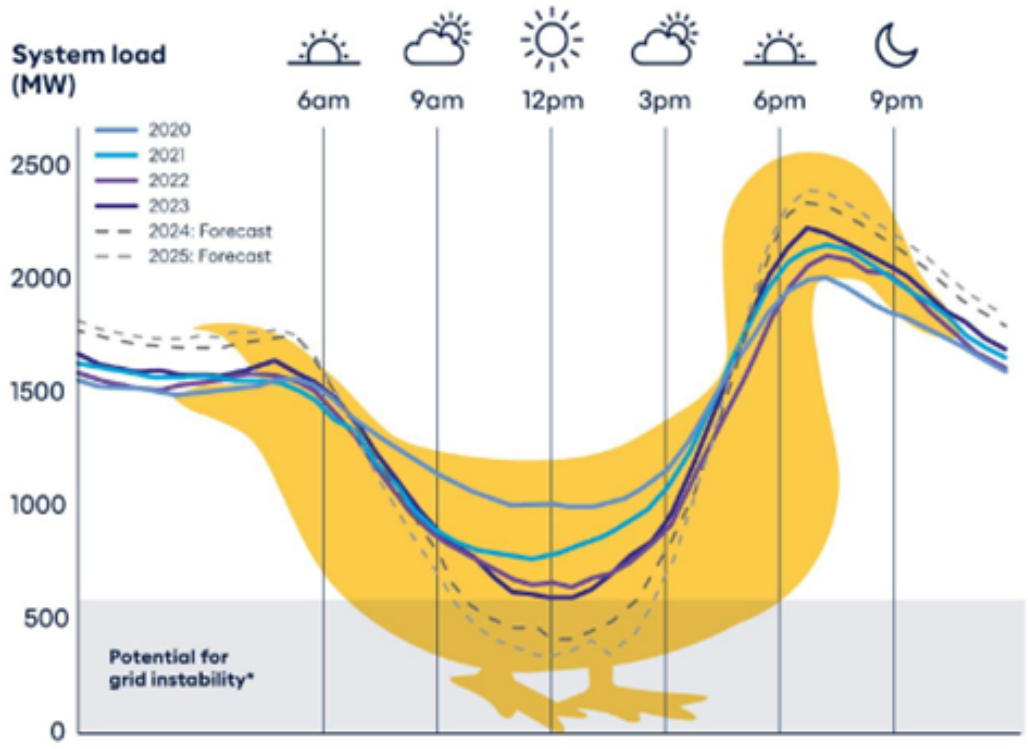


Figure 5. Example of a Duck Curve, Potential for grid instability * Grid instability refers to frequency and voltage deviations in the grid [50,51].

HRESs also align with the goals of the Just Energy Transition (JET) strategy, which aims to address inequality and promote economic diversification in coal-reliant provinces like Mpumalanga [28,30,42]. Decentralised hybrid systems enable small-scale renewable generation that can be community-owned and maintained, facilitating inclusive participation in energy governance [6,53].

Case studies from Limpopo and the Eastern Cape demonstrate the viability of PV–Biomass–Battery hybrids in advancing energy access, agricultural resilience, and economic inclusion [9,54,55]. These systems reduce energy poverty while simultaneously creating employment in system installation and maintenance [3,13,31].

In addition, HRES contribute directly to South Africa's Net Zero 2050 ambitions by enabling emission reductions through diesel substitution and reducing reliance on coal-based grid power [10,16,19]. Hybrid-powered green hydrogen systems, particularly in Northern Cape, offer a decarbonisation path for hard-to-abate sectors such as steel and chemicals [17,43,55].

2.5. Barriers to Scaling Hybrid Systems in South Africa

Despite technological maturity, HRES deployment faces significant structural barriers. Capital expenditure, especially for lithium-ion batteries and advanced EMS platforms, remains high, limiting access for small enterprises and municipalities [7,23,56]. Local manufacturers are also constrained by a weak supply chain and limited economies of scale [18,39,50].

Regulatory fragmentation between the Department of Mineral Resources and Energy (DMRE), Eskom, and the National Energy Regulator of South Africa (NERSA) often results in contradictory mandates and project delays [15,25,42]. Municipal utilities are particularly

under-resourced, facing aging infrastructure, poor financial health, and an inability to integrate embedded generation [20,49,57].

Societal acceptance is another concern. Without benefit-sharing models, HRES initiatives may trigger local resistance, especially in coal-dependent communities where economic insecurity remains high [19,21,40]. Lack of skills, training, and capacity within municipalities and cooperatives exacerbates operational risks [45,58,59].

Addressing these challenges requires coordinated governance reform, targeted subsidies for local manufacturers, concessional finance for community projects, and capacity building across all implementation tiers [13,22,60].

2.6. Policy and Regulatory Foundations for HRES Expansion

The 2021 amendment to Schedule 2 of the Electricity Regulation Act, which removed licensing for embedded generation projects up to 100 MW, catalysed a surge in HRES investment in the private sector [4,27,29]. Mining, agriculture, and industrial stakeholders have initiated over 5 GW of embedded capacity since the reform [8,9,47].

However, this expansion is still limited by legacy issues. Eskom controls grid access and transmission planning, while municipalities remain unable to sign Power Purchase Agreements (PPAs) under current procurement structures [15,25]. NERSA's regulatory reforms have not yet aligned municipal authority with market opportunities for decentralised energy [25,48].

The Just Energy Transition Implementation Plan (JET-IP) and supporting policies from the Presidential Climate Commission further affirm the role of decentralised HRESs in advancing equitable energy access [28,42,53]. Pilot projects in microgrid-based electrification, community-owned solar farms, and off-grid storage in Limpopo and Eastern Cape reflect this shift in institutional logic [6,54,55].

Global best practices, such as community cooperatives in Germany and India's rural solar hubs, underscore the importance of localised governance and hybridisation for energy resilience [2,41,60].

2.7. Strategic Role of HRESs in Energy Transition

HRESs are instrumental in reconciling technical performance with social equity. By reducing dependence on Eskom's centralised and unreliable grid, these systems enable energy sovereignty at household and community levels [5,10,44]. For regions like Mpumalanga, where over 120,000 jobs depend on the coal economy, HRESs offer alternative development paths through localised electrification, energy entrepreneurship, and workforce reskilling [19,28].

In Limpopo and Eastern Cape, PV–Biomass–Battery systems have powered water pumps, irrigation schemes, and rural agro-processing units, showing clear links between decentralised energy and improved livelihoods [45,54,55]. These applications are particularly important in enhancing gender equity, given the role of women in off-grid farming and household energy use [40,43,53].

Moreover, strategic investment in local training and manufacturing, for example in inverter assembly, solar panel installation, and microgrid monitoring, can enhance job creation, reduce import dependency, and improve technical support capacity across the country [25,51,61].

2.8. Summary

This review applied the MLP framework to examine how Hybrid Renewable Energy Systems (HRESs) support South Africa's energy transition. HRESs operate as niche innovations enabled by decentralised resources and pilot projects [1,3,39], while addressing regime-level constraints such as grid instability and rigid procurement frameworks [2,20].

Landscape shifts like climate pressure and falling technology costs further support their diffusion [39].

South Africa's renewable resource base and maturing technologies make HRES technically and economically viable [9,12,18]. These systems also align with national priorities for energy access, decarbonisation, and resilience [30,42,52].

The next chapter presents the research methodology designed to assess HRES viability through LCOE modelling, regime-level institutional analysis, and landscape scenario framing, aligned with the MLP framework.

3. Methodology

3.1. Methodological Approach and MLP Framework

This study applies a layered research design informed by the Multi-Level Perspective (MLP) to understand how Hybrid Renewable Energy Systems (HRESs) contribute to South Africa's energy transition [31,32]. Each analytical method aligns with a distinct MLP level. At the niche level, Levelised Cost of Electricity (LCOE) modelling is used to evaluate the techno-economic performance of three common hybrid system configurations—PV–Battery, PV–Diesel–Battery, and PV–Biomass–Battery—based on locally grounded assumptions [3,8]. The regime-level analysis identifies institutional and regulatory constraints that shape or inhibit HRES uptake, particularly those related to grid access, licensing, and procurement managed by actors such as Eskom, NERSA, and local municipalities [10,20]. At the landscape level, this study uses scenario framing to consider macro-level forces—such as load shedding, Just Energy Transition (JET) imperatives, and shifting global climate finance—that influence energy system change from outside the regime [39].

3.2. Niche-Level Analysis: LCOE Modelling of HRES

LCOE modelling is used to assess the financial viability of decentralised HRES configurations under South African conditions [3,8,18]. This study models three system types: PV–Battery, PV–Diesel–Battery, and PV–Biomass–Battery. Key parameters include a 20-year system lifetime, 8% discount rate, and technology-specific cost assumptions drawn from national and international sources [12,38,45]. Demand profiles reflect typical off-grid and weak-grid contexts. System optimisation incorporates performance characteristics such as battery round-trip efficiency, PV output variability, and diesel generator fuel curves [5,23].

To test the robustness of each configuration, sensitivity analysis is applied to variables like capital costs, fuel prices, and load levels [12,38,45]. This approach reflects the experimental nature of niche innovation: hybrid systems are tested across scenarios to evaluate performance under real-world uncertainty [3,18,39].

3.3. Regime-Level Assessment: Institutional and Policy Constraints

At the regime level, this study investigates institutional structures and policy frameworks that mediate the uptake of decentralised HRESs [10,20,26]. Key barriers include Eskom's market dominance, restrictive licensing rules enforced by NERSA, and the procurement systems that favour centralised projects. For instance, the single-buyer model discourages Independent Power Producers from supplying embedded generation solutions [14,57]. Municipalities also face legal ambiguity and resource constraints, which limit their ability to support or operate decentralised energy systems [6,17]. These insights are drawn from a review of national energy policy, legal instruments, and institutional mandates.

3.4. Landscape-Level Framing: Scenario and Policy Trend Analysis

At the landscape level, broader socio-economic and political forces are analysed to understand external pressures acting on the energy regime and influencing niche dynamics [2,31,39]. These include South Africa's national load shedding crisis, the JET investment plan, and growing international climate finance opportunities [30,35,42]. Scenario framing is used to contextualise the regime and niche findings within alternative futures, helping to clarify the conditions under which HRESs may scale and contribute to system-wide transformation.

3.5. Data Sources and Case Selection Criteria

Data inputs include peer-reviewed studies, national policy documents, municipal frameworks, and datasets from recognised energy research institutions. Emphasis is placed on studies using South African data or case-specific calibrations. Case selection prioritised technologies and sites that represent variation in geography, grid access, and policy relevance. This ensured that the analysis captured diverse conditions while remaining grounded in the local context [9,12,57].

3.6. Limitations

This study focuses on decentralised hybrid systems and does not cover utility-scale grid modelling. It is also policy-focused and does not include detailed simulations using tools such as HOMER, Matlab, or other advanced optimisation software. Limitations in data availability may affect the precision of LCOE outputs and institutional interpretations. Additionally, the selection of case studies and modelling assumptions may limit the generalisability of findings across South Africa's diverse energy landscapes. The exclusion of non-electrical energy solutions, such as thermal or transport energy, further narrows the scope. These constraints should be considered when interpreting the results and deriving policy implications.

4. Discussion

This section presents an integrated analysis of findings drawn from the technical evaluation of HRESs, institutional barriers, and macro-level dynamics influencing South Africa's energy transition. The structure aligns with the MLP framework, organising insights into three analytical levels: niche innovations, regime-level structures, and landscape-level pressures.

4.1. Niche-Level Results: Technical Viability of Hybrid Renewable Energy Systems (HRESs)

This study finds that HRESs are technically feasible and cost-effective across diverse South African applications, especially in rural and weak-grid contexts. Each configuration demonstrates the capacity to provide reliable, low-carbon electricity with high system availability, offering a viable alternative to centralised grid extension or diesel-only systems.

Hybrid systems deliver significant technical and operational benefits. Simulation and empirical evidence confirm that configurations such as PV–Battery, PV–Diesel–Battery, and PV–Wind–Battery consistently achieve system availabilities above 99% in off-grid and weak-grid areas [3,4]. For instance, PV–Diesel–Battery systems deployed in Limpopo clinics recorded a 30% increase in reliability and over 70% reduction in fuel costs compared to diesel-only baselines [7]. In mining operations in the Northern and North West provinces, PV–Wind–Battery hybrids significantly reduced diesel consumption and carbon tax exposure while ensuring stable power supply [5,6].

LCOE modelling reveals that PV–Battery and PV–Wind–Battery systems consistently produce electricity at a lower cost than Eskom's average tariff, which now exceeds

R1.30/kWh approximately (USD 0.07/kWh) [8,38]. PV–Diesel–Battery systems remain cost-competitive but are affected by operational fuel costs. PV–Hydrogen systems, while technologically viable, currently remain less competitive due to high capital costs associated with electrolysers, hydrogen storage infrastructure, and fuel cell systems. Moreover, round-trip conversion efficiency losses further elevate their LCOE [6,11]. However, emerging innovations and global cost declines in electrolyser technology may improve their viability in the medium to long term.

Equation (1), which defines the Levelised Cost of Electricity (LCOE), is adapted from internationally recognised methodologies developed by IRENA [39], HOMER modelling guidelines [49], and the IEA [46]. It integrates annualised CAPEX, OPEX, and energy generation values over the assumed project lifetime and serves as the central metric for cost–performance analysis in this study.

$$\text{LCOE} = \frac{\sum_{t=1}^{n} (\text{CAPEX}_t + \text{OPEX}_t)/(1+r)^t}{\sum_{t=1}^{n} E_t/(1+r)^t} \quad (1)$$

where

- CAPEX_t is the capital expenditure in year t;
- OPEX_t is the operating expenditure in year t;
- E_t is the energy generated in year t;
- r is the discount rate;
- n is the system lifetime (in years).

While detailed simulations fall outside the scope of this policy-focused paper, Equations (2) to (23) are presented to show how system-level feasibility and performance trade-offs can be analysed. These are adapted from internationally recognised modelling frameworks and empirical studies, including [25,39,46,49,62].

PV–Battery Systems:

$$P = A \cdot G \cdot \eta \quad (2)$$

$$n_{\text{round}} = n_{\text{charge}} \cdot n_{\text{discharge}} \quad (3)$$

$$E_{\text{storage}} = (D \cdot L_{\text{daily}})/n_{\text{round}} \quad (4)$$

$$C_{\text{PV-Batt}} = (c_{\text{pv}} \cdot P_{\text{pv}}) + (c_{\text{batt}} \cdot E_{\text{storage}}) \quad (5)$$

$$\text{O\&M} = \alpha_{\text{pv}} \cdot C_{\text{PV}} + \alpha_{\text{batt}} \cdot C_{\text{Battery}} \quad (6)$$

Equations (2) to (6) are widely applied in estimating photovoltaic energy output based on irradiance and panel area, with tools such as PV system and HOMER incorporating it as a core computational input [12,13]. Regions like the Northern Cape experience solar irradiation levels above 6 kWh/m^2/day, making PV–battery systems particularly attractive [14]. Battery efficiency, governed by Equation (2), is a key determinant of system losses. In field trials across Limpopo clinics, lithium-iron phosphate $LiFePO_4$ batteries exhibited round-trip efficiencies above 85%, directly impacting system LCOE [15].

PV–Diesel–Battery Systems:

$$F = \frac{E}{(\eta_{\text{genset}} \cdot \rho \cdot \text{LHV})} \quad (7)$$

$$\text{SDR} = \frac{E_{\text{PV+Battery}}}{E_{\text{Diesel_Base_Case}}} \quad (8)$$

$$C_{\text{Hybrid}} = C_{\text{PV}} + C_{\text{Battery}} + C_{\text{Genset}} \quad (9)$$

$$\text{OPEX}_{\text{fuel}} = F \cdot c_{\text{diesel}} + c_{\text{genset}} \cdot C_{\text{Genset}} \tag{10}$$

Equations (7) to (10) allow for accurate fuel use projections, considering generator efficiency and diesel properties, critical for cost modelling in off-grid deployments [16]. The Diesel Displacement Ratio in Equation (8) is a widely used metric for assessing the renewable contribution of hybrid systems. Projects in Mpumalanga and the Eastern Cape have demonstrated SDR values exceeding 0.65, resulting in significant diesel cost savings and emission reductions [17,18].

PV–Wind–Battery Systems:

$$P_{\text{wind}} = 0.5 \cdot \rho \cdot A \cdot v^3 \cdot C_p \tag{11}$$

$$P_{\text{total}} = P_{\text{PV}} + P_{\text{wind}} \tag{12}$$

$$C_{\text{PV-Wind-Batt}} = C_{\text{PV}} + C_{\text{Battery}} + (c_{\text{wind}} \cdot P_{\text{wind}}) \tag{13}$$

$$\text{O\&M}_{\text{wind}} = \alpha_{\text{wind}} \cdot C_{\text{wind}} \tag{14}$$

Wind generation potential, evaluated via Equation (11), shows strong seasonality and geographic dependency. In coastal areas of the Western and Eastern Cape, average wind speeds above 6 m/s support viable small-scale wind integration [19,20]. Equation (11), which aggregates PV and wind generation, is commonly used in hybrid simulations to optimise generation mix and load matching. These configurations have proven effective in smoothing supply variability and reducing the need for oversized battery banks [21].

PV–Biomass–Battery Systems:

$$E_{\text{biomass}} = m \cdot \text{LHV}_{\text{biomass}} \cdot \eta_{\text{biogen}} \tag{15}$$

$$C_{\text{Biomass}} = C_{\text{PV}} + C_{\text{Battery}} + C_{\text{Biogen}} \tag{16}$$

$$\text{O\&M} = \alpha_{\text{bio}} \cdot C_{\text{Biogen}} + \text{fuel handling, maintenance} \tag{17}$$

PV–Biomass–Battery systems offer dispatchable renewable power using locally available feedstock, making them suitable for rural electrification and agricultural hubs. These systems align with South Africa's Bioenergy Atlas and the Department of Science and Innovation's Bioenergy Strategy, which promotes biomass use for off-grid and mini-grid contexts [39]. While technical viability is established (Equations (15)–(17)), challenges include fuel logistics, seasonal feedstock availability, and maintenance demands, especially where supply chains are informal or underdeveloped.

PV–Hydrogen Systems:

$$\text{H}_2 = \frac{(P_{\text{electrolyser}} \cdot t)}{E_{\text{H}_2}} \tag{18}$$

$$C_{\text{Hydrogen}} = C_{\text{PV}} + C_{\text{Electrolyser}} + C_{\text{Storage}} + C_{\text{FuelCell}} \tag{19}$$

$$\text{O\&M} = \alpha_{\text{elec}} \cdot C_{\text{Electrolyser}} + \text{compression} + \text{safety} \tag{20}$$

Equations (18) to (20) govern hydrogen production via electrolysis and are gaining relevance in long-duration energy storage applications. The Hydrogen South Africa (HySA) programme and pilot projects in Saldanha Bay and Secunda are evaluating the use of surplus PV and wind to power electrolysers for green hydrogen production [22,23]. While still at the demonstration stage, hydrogen-integrated systems are expected to support industrial decarbonisation in fertiliser, synthetic fuel, and steel production sectors [25].

Multi-Source EMS-Controlled Systems:

$$\sum P_{\text{gen}} + P_{\text{batt.discharge}} = P_{\text{load}} + P_{\text{batt.charge}} + P_{\text{loss}} \quad (21)$$

$$C_{\text{EMS}} = c_{\text{EMS}} \cdot N_{\text{nodes}} + C_{\text{integration}} \quad (22)$$

$$\text{O\&M} = \alpha_{\text{IT}} \cdot C_{\text{EMS}} + \text{system support staff} \quad (23)$$

Equations (21) to (23) form the basis of dispatch control in EMS platforms, ensuring real-time balancing between generation, load, storage, and losses. AI-enabled EMSs have been piloted in off-grid sites in the northwest and KwaZulu-Natal, where they improved operational efficiency by up to 20% compared to traditional control systems [26]. The ability to dynamically allocate generation and storage capacity according to real-time demand has emerged as a key enabler of resilient microgrids [27].

These formulas enable streamlined system modelling for diverse applications. Equation (5) informs CAPEX forecasts for PV–Battery systems, Equation (10) estimates diesel fuel costs, Equation (13) supports wind–solar capital planning, and Equation (23) guides O&M budgeting for EMS integration. Collectively, they support component sizing, lifecycle cost estimation, fuel displacement analysis, and system integration planning.

These formulas enable streamlined system modelling for diverse applications. Table 1 below summarises key trade-offs across system configurations, linking technical features to their cost and operational implications.

Table 1. Summary of cost-based technical trade-offs by HRES configuration (sources: Author adapted from [39,41,46,49,62]).

System Type	Advantages	Trade-Offs
PV–Battery	Low emissions, low O&M, modular	High upfront CAPEX for storage; reduced performance in areas with poor load matching [43]
PV–Diesel–Battery	Reliable dispatchable backup; reduced outages	Fuel dependency, emissions, higher OPEX; lower renewable share [57]
PV–Wind–Battery	Seasonal/diurnal synergy; reduced fuel needs	Complex O&M, turbine siting constraints, mechanical wear [45]
PV–Hydrogen	Long-duration storage; industrial applicability	High CAPEX, low round-trip efficiency, commercially viable only at scale [60]
EMS-Controlled Systems	Improved load balancing; automated control	Requires advanced ICT, skilled maintenance, and reliable data in low-resource contexts [44]

To supplement the qualitative trade-off summary above, Table 2 presents a comparative matrix evaluating each HRES configuration against five key performance and cost dimensions: fuel dependency, reliability, renewable fraction, capital expenditure (CAPEX), and operations and maintenance (O&M) cost. This visual format enables rapid assessment of configuration suitability based on technical context and investment constraints.

The hybrid configurations modelled here also align with national energy policy priorities. PV–Battery and PV–Diesel–Battery systems directly support rural electrification goals set out in the Department of Mineral Resources and Energy's (DMRE) Energy Access Strategy [45]. PV–Hydrogen hybrids, though currently less cost-competitive, correspond with the Green Hydrogen Commercialisation Strategy, which positions South Africa as a global green hydrogen hub [60]. Meanwhile, EMS-based microgrids complement the Just Energy Transition (JET) framework by promoting decentralised energy access and resilience in underserved areas [44]. These linkages reinforce the policy relevance of HRESs for South Africa's low-carbon development pathway.

Table 2. Comparative matrix of HRES configurations across key criteria (sources: Author adapted from [39,41,46,49,62]).

Performance Criteria	PV–Battery	PV–Diesel–Battery	PV–Wind–Battery	PV–Hydrogen	Multi-Source + EMS
Fuel Dependency	None	Medium–High	None	None	Variable
Reliability	Moderate	High	High	High	Very High
Renewable Fraction	High	Moderate	High	Very High	High
CAPEX	High	Medium	High	Very High	High
O&M Cost	Low	Medium–High	High	Very High	Medium

4.2. Regime-Level Results: Constraints in South Africa's Centralised Energy System

Despite the technical viability of Hybrid Renewable Energy Systems (HRESs), their adoption in South Africa is hindered by persistent regime-level barriers. These structural constraints reflect institutional lock-in, regulatory delays, and procurement misalignment within the centralised energy regime dominated by Eskom and national planning authorities.

A key constraint is the misalignment between decentralised HRES capabilities and centralised procurement mechanisms. While policy revisions, such as Schedule 2 amendments to the Electricity Regulation Act, now exempt sub-100 MW projects from licensing, municipalities and small-scale IPPs still face slow grid connection approvals, limited wheeling frameworks, and unclear revenue models [18,19].

The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), while successful for utility-scale renewables, does not accommodate hybrid mini-grids or embedded generation suitable for remote or informal areas [20]. Consequently, niche HRES applications remain disconnected from formal funding and grid integration pathways.

Institutional fragmentation further impedes rollout [21]. Municipal energy offices, though constitutionally mandated to provide basic electricity services, often lack procurement authority or technical capacity to manage hybrid systems. Coordination gaps between the DMRE, Eskom, NERSA, and municipal governments create implementation uncertainty, particularly in informal settlements or off-grid public infrastructure [22].

Additionally, cost recovery remains a structural barrier. Tariff structures do not reflect the avoided costs or resilience benefits of HRESs. Without integrated municipal financial models that account for lifecycle O&M and fuel savings (as quantified in Equations (5) to (23)), long-term viability remains uncertain [23].

Together, these regime-level constraints highlight the disconnect between demonstrated technical potential and institutional readiness [19–23,25]. Addressing this gap requires reforms that mainstream hybrid systems into procurement frameworks, decentralised planning, and municipal budgeting practices aligned with the Just Energy Transition.

4.3. Landscape-Level Results: National Energy Crisis and External Pressures

At the macro-level, South Africa's energy transition is shaped by structural pressures that extend beyond sector-specific interventions. These include economic volatility, public demand for energy justice, worsening grid unreliability, and mounting international expectations around decarbonisation. Together, these external drivers amplify the urgency of adopting distributed Hybrid Renewable Energy Systems (HRESs), particularly in areas underserved by the national grid.

Frequent load shedding, averaging over 200 days per year since 2022, has exposed the fragility of Eskom's centralised grid, disrupting service delivery and deterring investment [26]. In response, municipalities and other actors are increasingly pursuing off-grid

and embedded generation options such as PV–Battery and PV–Wind–Battery systems to support public facilities and commercial activity [27].

Internationally, South Africa faces growing pressure to accelerate its energy transition through climate finance mechanisms and trade-linked decarbonisation expectations. The USD 8.5 billion Just Energy Transition (JET) partnership and related financing instruments incentivise modular, clean-energy infrastructure with equitable development co-benefits [28,29]. HRESs align with these objectives by supporting universal access, local job creation, and fossil fuel displacement.

Macroeconomic variables further shape system viability. Rising fuel prices, local currency depreciation, and global equipment shortages have made diesel and gas-based generation costlier. In this context, configurations with higher upfront capital expenditure but lower operational costs, such as PV–Battery systems, may prove more viable over a 15–20 year planning horizon, especially if public subsidies or blended finance mechanisms are introduced [30].

At the social level, public frustration with persistent outages, rising electricity costs, and environmental degradation has driven demand for decentralised, community-oriented solutions. Civil society movements increasingly advocate for energy sovereignty and resilience, with growing support for inclusive planning processes that prioritise marginalised communities [42].

These landscape-level factors collectively reinforce the importance of enabling conditions, such as stable financing, supportive policy signals, and social acceptance, for mainstreaming HRESs into South Africa's broader development and infrastructure agenda.

4.4. Systemic Barriers to HRES Deployment

This subsection summarises the structural, institutional, and socio-political constraints affecting HRES deployment, aligned to the MLP framework introduced in Section 3. The barriers are grouped by niche, regime, and landscape levels, offering a layered understanding of implementation obstacles beyond technical performance.

Cross-Cutting Barriers

Niche-Level Obstacles: High upfront costs for lithium-ion batteries, EMS platforms, and grid-compliant inverters restrict small-scale and community-led project development [10–12,29]. Access to concessional finance is limited by credit and currency risks, concentrating market activity among large private actors and reducing local experimentation.

Regime-Level Misalignments: Fragmentation across DMRE, Eskom, NERSA, and municipalities results in policy incoherence and delayed implementation [1–8]. Grid bottlenecks in high-resource provinces and the slow rollout of reforms like Schedule 2 licensing changes further constrain hybrid integration.

Landscape-Level Pressures: Socio-political tensions and economic instability reduce public trust and absorptive capacity [13–18]. Under-resourced municipalities struggle with debt and infrastructure backlogs. In coal-dependent areas, the transition is often perceived as externally imposed and inequitable.

This layered assessment underscores the systemic nature of HRES barriers and the need for coordinated, multi-scalar responses (Table 3).

Table 3. Mapping of systemic barriers to MLP levels [58].

MLP Level	Barrier Category	Key Issues Identified
Niche Level	Financial Constraints and Market Risk	High CAPEX; lack of concessional finance; currency volatility; limited access for small/community-led projects [9–12]. Dominance of large actors; low experimentation and local learning [9–12].
Regime Level	Infrastructure and Grid Limitations	Aging grid; outdated architecture; limited transmission capacity in high-resource provinces [1–4].
	Policy and Regulatory Fragmentation	Overlapping mandates; REIPPPP delays; inconsistent implementation; weak municipal enforcement capacity [5–8].
	Municipal Dysfunction and Distribution Gaps	Poor revenue collection; technical and institutional incapacity; tariff misalignment; legacy debt [13,16,17].
Landscape Level	Social Resistance and Equity Challenges	Transition viewed as externally driven; job losses in coal regions; limited community benefit; energy poverty; spatial inequality [16–19].

5. Policy and Institutional Recommendations

To support a structured and inclusive policy transition towards HRESs in South Africa, this section presents a set of targeted policy and institutional recommendations. These are grounded in the empirical findings of this study and framed within the MLP to address challenges at the niche, regime, and landscape levels. The recommendations are also explicitly aligned with the study's research objectives:

- Objective 1: Assess the technical and economic feasibility of HRESs using LCOE models grounded in local conditions.
- Objective 2: Analyse institutional, regulatory, and governance barriers.
- Objective 3: Apply the MLP framework to interpret multi-level transition dynamics.
- Objective 4: Propose regionally specific and policy-relevant recommendations to support an inclusive and decentralised energy transition.

This section presents strategic HRES recommendations for five key provinces, emphasising techno-economic viability and socio-environmental alignment. In addition to these region-specific proposals, a set of cross-cutting national actions is included to support and coordinate HRES deployment across all levels. Although this study did not conduct original feasibility modelling, it conceptually addresses Objective 1 by outlining how tools like LCOE modelling could guide the selection of HRES configurations. This framing supports the development of regionally tailored and nationally relevant recommendations.

5.1. Mpumalanga: Repurposing the Coal Belt

The selection of PV–Battery systems in Mpumalanga draws on the feasibility framing outlined under Objective 1. While this study did not conduct original LCOE modelling, it highlights how such analysis could be applied to validate the cost-effectiveness of hybrid systems that leverage existing coal infrastructure and transmission assets. The policy dynamics in Mpumalanga engage with the regime and landscape levels of the Multi-Level Perspective (MLP) framework. This analysis directly contributes to Objectives 2 and 4 of the study, which focus on identifying governance barriers and proposing regionally relevant policy responses.

Mpumalanga, historically the center of South Africa's coal-fired power generation, faces urgent socio-economic risks as coal infrastructure is decommissioned. Over 120,000 jobs are linked to the coal value chain in this province alone [1]. The introduction of PV–Battery systems integrated with Grid Energy Management Systems (EMSs) offers a path to decarbonise while leveraging the existing transmission infrastructure. These hybrid systems can be installed on repurposed coal plant sites, minimising land-use conflicts and transmission losses.

However, labour resistance, strong union presence, and fears of economic displacement continue to challenge implementation. As noted by the Presidential Climate Commission, retraining and reintegration programmes are essential for garnering community buy-in [2].

A suitable hybrid configuration for this context is PV combined with Battery and Grid EMS. The rationale for this recommendation lies in the ability to repurpose decommissioned coal infrastructure while enabling local job retraining. The main barrier remains labour resistance and union lobbying.

5.2. Northern Cape: Hydrogen and Export-Driven Hybridisation

The proposed PV–Wind–Hydrogen system reflects Objective 1 by illustrating how feasibility studies, if conducted, could validate this configuration's suitability in high-resource provinces like the Northern Cape.

The analysis of the Northern Cape focuses on the niche and landscape levels of the Multi-Level Perspective (MLP). These insights directly align with Objectives 3 and 4, which relate to interpreting transition dynamics and offering policy-relevant recommendations.

The Northern Cape is South Africa's solar and wind powerhouse, receiving some of the highest solar irradiance globally and steady wind profiles conducive to hybridisation [3]. This region is also strategically positioned for green hydrogen production, especially near the Port of Saldanha, which facilitates potential export markets [4]. PV–Wind–Hydrogen systems are being piloted for both domestic supply and international hydrogen value chains.

Yet, grid congestion and the lack of a clear national hydrogen framework hinder full-scale deployment. Targeted investment in electrolyser infrastructure and updated grid codes would enable greater utilisation of the province's renewable potential [5].

The recommended hybrid system is PV with Wind and Hydrogen. This is based on the province's strong solar–wind synergy and port access, which make it ideal for green hydrogen exports. Grid congestion and the absence of a national hydrogen strategy remain key barriers.

5.3. Eastern Cape: Agro-Energy Integration

This case aligns with Objective 1 by demonstrating how future feasibility assessments could support the deployment of agro-energy hybrid systems tailored to the Eastern Cape's agricultural context.

This regional case study reflects interactions at both the niche and regime levels of the MLP framework. It contributes directly to Objectives 2 and 4 by analysing governance constraints and developing locally grounded energy policy recommendations.

The Eastern Cape holds significant potential for biomass-integrated hybrid systems due to its robust agricultural sector. PV–Biomass–Battery systems offer a dual advantage: electricity generation and agro-waste valorisation [6]. In areas such as the Amathole and Alfred Nzo districts, small-scale hybrid systems have shown promise in powering rural co-operatives and food processing units.

These systems contribute to energy access and economic development, especially where the grid remains unreliable. However, challenges related to commercialisation, technology availability, and financing for biomass conversion persist [7]. The recommended configuration for the Eastern Cape is PV combined with Biomass and Battery. This aligns with the region's agro-waste potential, offering co-generation benefits and employment opportunities. The major barrier is a lack of commercialisation experience.

5.4. Limpopo: Rural Electrification and Public Service Resilience

While this study did not undertake LCOE modelling, the policy recommendations for Limpopo are aligned with Objective 1, as they suggest how feasibility analysis could be used to justify PV–Diesel–Battery deployment in underserved rural areas.

The situation in Limpopo involves key regime and landscape-level dynamics, as defined by the MLP framework. This case is used to meet Objectives 2 and 4 by examining institutional challenges and recommending inclusive transition measures for rural public services.

Limpopo's energy profile is characterised by high rurality and limited grid coverage. PV–Diesel–Battery hybrids have been deployed successfully in health clinics and educational institutions to enhance reliability and reduce diesel dependency [8]. These systems deliver critical services uninterrupted during load shedding and grid outages. Despite strong technical feasibility, limited operations-and-maintenance capacity and financing constraints limit scalability. Development finance institutions and public–private partnerships could help mainstream these configurations in public infrastructure [9].

The most suitable hybrid option in Limpopo is PV combined with Diesel and Battery. This setup supports rural electrification for clinics, schools, and cooperatives. However, financing limitations and insufficient O&M capacity hinder broader implementation.

5.5. Gauteng: Urban Decarbonisation and Mobility Integration

In alignment with Objective 1, this case reflects how feasibility considerations could inform the choice of urban HRES systems. Although no original modelling was performed, the study outlines the rationale for PV–Battery and EV integration in Gauteng's high-density settings.

Gauteng's urban energy context is analysed through the niche and regime levels of the MLP framework. This case directly contributes to Objectives 3 and 4 by examining innovation–system interactions and proposing urban-focused decarbonisation policies. Gauteng, the country's most industrialised and urbanised province, presents opportunities for smart urban energy systems. PV–Battery systems integrated with EV charging stations are well-aligned with urban decarbonisation goals and emerging transport electrification trends [10]. Rooftop solar on commercial buildings and residential developments, combined with local storage and demand-side management, can significantly reduce pressure on the Eskom grid during peak hours. However, constraints such as grid saturation, building code limitations, and the high cost of battery technologies still hinder widespread deployment [3].

The recommended configuration for Gauteng includes PV with Battery and EV Charging. This system enables urban decarbonisation while supporting electric mobility infrastructure. Market readiness for EVs and high storage costs are notable barriers.

5.6. Cross-Cutting Institutional and Policy Reforms

This section addresses all three levels of the MLP framework—niche, regime, and landscape—and integrates findings to support Objectives 2, 3, and 4. It identifies overarching governance reforms needed to unify and scale the regional recommendations proposed earlier.

In addition to the provincial strategies, system-wide interventions are essential to enable coordinated and scaled deployment of HRESs. Recommendations:

- The institutional mandates of key actors such as DMRE, DCOG, SALGA, NERSA, and municipalities should be clarified to remove regulatory duplication and enhance municipal authority in energy decision-making [11].
- Procurement frameworks must be reformed, and licensing procedures streamlined to support distributed and small-scale HRESs [12].
- A National HRES Coordination Platform should be established to align public and private actors and track progress under the Just Energy Transition Implementation Plan [2].
- Financing instruments must be expanded through blended finance models, targeted subsidies, and climate-linked funds administered under a central Hybrid Energy Infrastructure Facility [9].
- Municipal capacity should be strengthened through technical training, integrated planning systems, and national knowledge-sharing hubs that promote HRES best practices [13].

6. Conclusions

HRESs offer a strategic and technically sound pathway for South Africa to meet the targets outlined in the IRP 2019, the Net Zero 2050 commitment, and the Just Energy Transition framework. Their modularity, declining LCOE, and ability to integrate variable renewable energy sources such as solar and wind with dispatchable components like storage and biomass make them particularly suitable for the country's fragmented and reliability-constrained electricity grid.

Framed through the MLP, this study has demonstrated that the viability of HRESs depends not only on niche-level technology performance but also on regime-level institutional coherence and landscape-level structural conditions. Regime challenges such as transmission limitations, regulatory misalignment, and municipal dysfunction intersect with landscape pressures like economic instability and social resistance. These barriers collectively constrain the pace and inclusivity of HRES deployment.

Addressing these challenges requires multi-level policy coordination, targeted financial mechanisms, and socially inclusive governance models. Strategic interventions must simultaneously strengthen niche experimentation, reform regime structures, and adapt to landscape shifts.

Ultimately, the transformative potential of HRESs will be measured not just by installed renewable capacity, but by their contribution to a just, inclusive, and systemically integrated energy transition in South Africa, where niche innovations scale within enabling regimes and resilient landscapes.

Author Contributions: Conceptualisation, M.M., X.Y. and M.S.; writing—original draft preparation, M.M.; writing—review and editing, M.M. and X.Y.; supervision, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research recieve no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The Department of Electrical and Smart Systems Engineering is acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Swilling, M.; Musango, J.; Wakeford, J. Developmental states and sustainability transitions: Prospects of a just transition in South Africa. *J. Environ. Policy Plan.* **2016**, *18*, 650–672. [CrossRef]
2. United Nations. The Future We Want: Resolution Adopted by the General Assembly, Rio de Janeiro. 2012. Available online: https://sustainabledevelopment.un.org/futurewewant.html (accessed on 12 May 2025).
3. Department of Environmental Affairs. *National Climate Change Response White Paper*; Department of Environmental Affairs: Pretoria, South Africa, 2013. Available online: https://www.gov.za/sites/default/files/gcis_document/201409/nationalclimatechangeresponsewhitepaper0.pdf (accessed on 14 May 2025).
4. Department of Energy. *Integrated Resource Plan for Electricity 2010–2030*; Department of Energy: Pretoria, South Africa, 2011. Available online: https://www.energy.gov.za/IRP/irp-update-draft-report-2011.html (accessed on 14 May 2025).
5. Coyle, R.G. *System Dynamics Modelling: A Practical Approach*; Chapman and Hall/CRC: Boca Raton, FL, USA, 1996.
6. Abiri-Franklin, S.O.; Onuoha, C.F.; Afolalu, S.A.; Agada, J.N.; Olarinde, E.S. Evaluating legal frameworks for hydrogen energy storage in Sub-Saharan Africa: Policy principles and economic perspectives. In Proceedings of the 2024 International Conference on Science, Engineering and Business for Driving Sustainable Development Goals (SEB4SDG), Omu-Aran, Nigeria, 2–4 April 2024; pp. 1–6.
7. Xamlashe, T.; Monchusi, B.B.; Tshibanda, M. Design and Implementation of a PV–Battery System. In Proceedings of the 2023 International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town, South Africa, 16–17 November 2023. [CrossRef]
8. Matlou, M.; Smith, J.; Nkosi, T.; Chen, L.; Patel, R.; Gomez, A. Hybrid renewable energy system optimization for rural applications. *Energy Rep.* **2020**, *6*.
9. International Renewable Energy Agency (IRENA). Hybrid Power Systems for Off-Grid Applications. 2022. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/SDG7_Tracking_Progress_2022.pdf (accessed on 17 May 2025).
10. United Nations Environment Programme (UNEP). Emissions Gap Report 2023. 2023. Available online: https://www.unep.org/resources/emissions-gap-report-2023 (accessed on 11 May 2025).
11. World Meteorological Organization (WMO). State of the Global Climate 2023. 2024. Available online: https://wmo.int/publication-series/state-of-global-climate-2024 (accessed on 20 May 2025).
12. Department of Mineral Resources and Energy (DMRE). Integrated Resource Plan 2019. 2019. Available online: https://www.dmre.gov.za/Portals/0/Energy_Website/IRP/2019/IRP-2019.pdf (accessed on 18 May 2025).
13. Organisation for Economic Co-Operation and Development (OECD). Distributional Impacts of Energy Transition. 2024. Available online: https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/09/distributional-impacts-of-energy-transition-pathways-and-climate-change_212834fc/56e93f3e-en.pdf (accessed on 23 May 2025).
14. Energy Systems Research Group. *Electricity Transition Analysis*; Technical Report; University of Cape Town: Cape Town, South Africa, 2022.
15. National Energy Regulator of South Africa (NERSA). Annual Electricity Industry Report. 2023. Available online: https://www.nersa.org.za (accessed on 21 May 2025).
16. World Bank. *South Africa Climate Investment Plan*; Report; World Bank: Johannesburg, South Africa, 2023. Available online: https://www.worldbank.org (accessed on 20 May 2025).
17. Technical Working Group (TWG). *Green Hydrogen Potential in SA*; Technical Working Group (TWG)—University of Capetown: Capetown, South Africa, 2021.
18. Smil, V. *Energy Transitions: Global and National Perspectives*; Praeger: Santa Barbara, CA, USA, 2017.
19. Kumar, A.; Höffken, J.I.; Pols, A. *Dilemmas of Energy Transitions in the Global South: Balancing Urgency and Justice*; Taylor & Francis: Boca Raton, FL, USA, 2021.
20. Vavilov, D. *Narratives of Energy Transition*; Scholarworks; UMass Boston: Boston, MA, USA, 2020.
21. Development Bank of Southern Africa (DBSA). *Green Infrastructure Projects*; Development Bank of Southern Africa (DBSA): Midrand, South Africa, 2023.
22. Council for Scientific and Industrial Research (CSIR). Historical Cost of Electricity in South Africa. 2022. Available online: https://www.csir.co.za/csir-releases-statistics-on-power-generation-south-africa-2022 (accessed on 13 May 2025).
23. Dufo-López, R.; Bernal-Agustín, J.L.; Yusta-Loyo, J.M.; Domínguez-Navarro, J.A.; Ramírez-Rosado, I.J.; Lujano, J.; Aso, I. EMS optimization in standalone hybrid systems. *Renew. Sustain. Energy Rev.* **2014**, *29*, 728–743. [CrossRef]
24. Centre for Renewable and Sustainable Energy Studies (CRSES). Stellenbosch University. 2025. Available online: https://www.crses.sun.ac.za (accessed on 24 May 2025).
25. Eberhard, A. Electricity Planning and Regulatory Reform. 2023. Available online: https://www.gsb.uct.ac.za (accessed on 17 May 2025).

26. Energy Transitions Commission (ETC). Energy Transitions in South Africa. 2020. Available online: https://www.energy-transitions.org (accessed on 15 May 2025).
27. Bloomberg New Energy Finance (BNEF). Energy Transition Investment Trends. 2023. Available online: https://about.bnef.com (accessed on 16 May 2025).
28. Presidential Climate Commission. Just Energy Transition Implementation Plan 2023–2027. 2023. Available online: https://www.stateofthenation.gov.za/assets/downloads/JET%20Implementation%20Plan%202023-2027.pdf (accessed on 10 May 2025).
29. International Renewable Energy Agency (IRENA). World Energy Transitions Outlook 2022. 2022. Available online: https://www.irena.org (accessed on 12 April 2025).
30. Trade & Industrial Policy Strategies (TIPS). *Just Transition Progress Report 2023*; Technical Report; Trade & Industrial Policy Strategies: Pretoria, South Africa, 2023.
31. Swilling, M.; Franceys, R.; Kritzinger, K.; Musango, J.K.; Brent, A.; Tait, L.; McCulloch, M.; Naudé, M.; Sebitosi, A.B. Fostering Sustainable Transitions for South Africa's Electricity Sector. *J. Environ. Policy Plan.* **2023**.
32. Geels, F.W.; Kern, F.; Clark, W.C. Sustainability transitions in consumption-production systems. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2310070120. [CrossRef] [PubMed]
33. Nhamo, A.; Sibanda, L.M.; Mjimba, K.T. Transformation of South Africa's energy landscape: Policy, politics, and power dynamics. *Renew. Energy Focus* **2025**, *44*, 35–46.
34. Gumede, T.; Musango, S. Institutional quality and energy transitions: Insights from South Africa's decentralised renewable energy trajectory. *Int. J. Sustain. Energy Plan. Manag.* **2023**, *40*, 89–102.
35. World Economic Forum. *Mobilizing Clean Energy Investments in South Africa*; Technical Report; World Economic Forum: Geneva, Switzerland, 2024.
36. Climate Transparency. *Implementation Check: South Africa Energy Transition*; Technical Report; Climate Transparency: Johannesburg, South Africa, 2023.
37. Genus, A.; Coles, A.M. Rethinking the Multi-Level Perspective of Technological Transitions. *Res. Policy* **2008**, *37*, 1436–1445. [CrossRef]
38. IRENA. *Hybrid Power Systems for Off-Grid Applications*; IRENA: Masdar City, United Arab Emirates, 2022.
39. Hartmann, D. Challenges of Sustainable Energy Transition. *Energy Rep.* **2023**, *9*, 1–12. [CrossRef]
40. Sovacool, B.K. Energy Transitions and the Power of Policy. *Land* **2022**, *11*, 120. [CrossRef]
41. International Energy Agency (IEA); World Economic Forum (WEF). *Perspectives for the Energy Transition: Energy Efficiency 2022*; Technical Report; IEA; WEF: Paris, France, 2022.
42. Pueyo, A.; Leining, C. *Just Transition Processes: From Theory to Practice*; Report; Motu Economic and Public Policy Research: Wellington, New Zealand, 2023.
43. York, R.; Bell, S.E. Energy Transition or Addition? *Soc. Curr.* **2023**, *11*, 4–22. [CrossRef]
44. Godin, B.; Schmidt, B.; Lovins, A.; Myers, N.; Hicks, B.; Jones, J.; Baxter, J. The Rise of Renewables and Energy Transition: What Adaptation Strategy for Oil Companies and Oil Exporting Countries? *Middle East Policy* **2019**, *26*, 131–145. [CrossRef]
45. Gaye, M. *Transcript: Energy Transformation in Global South*; Transcript Verlag: Bielefeld, Germany, 2020.
46. Baker, L.; Phillips, J. *Linking the Energy Transition and Economic Development*; Technical Report; Energy Research Centre, University of Cape Town: Cape Town, South Africa, 2023.
47. World Economic Forum. *Energy Transition 101*; Report; World Economic Forum: Geneva, Switzerland, 2020.
48. Sadorsky, P. Economic Aspects of the Energy Transition. *Energies* **2023**, *16*, 2965. [CrossRef]
49. Nhamo, G.; Mpofu, B.; Muchuru, S. Coal Dependency and the Politics of Energy Transition in South Africa. *Energy Policy* **2024**, *185*, 113103. [CrossRef]
50. Van Niekerk, H. *South Africa's Coal Exit: Stakeholder Perspectives*; Technical Report; Stockholm Environment Institute: Stockholm, Sweden, 2024. Available online: https://www.sei.org/wp-content/uploads/2024/09/just-transition-coal-south-africa.pdf (accessed on 10 May 2025).
51. Corbet, S.; Larkin, C.; Lucey, B.; Meegan, A.; Yarovaya, L. Volatility Spillovers in Energy Markets During COVID-19. *Energy Econ.* **2021**, *104*, 105623. [CrossRef]
52. World Economic Forum. *Fostering Effective Energy Transition 2024*; Technical Report; World Economic Forum: Geneva, Switzerland, 2024.
53. Via, C. Just Energy Transition and Infrastructure. viac060. 2022. Available online: https://justenergytransition.co.za/ (accessed on 10 May 2025).
54. Agyepong, A.; Taliotis, C.; Howells, M.; Moksnes, N.; Rogner, H.H.; Bazilian, M.; Welsch, M. Sustainability Pathways for African Power Systems. *Sustainability* **2023**, *15*, 3123. [CrossRef]
55. Tladi, B.; Kambule, N.; Modley, L.-A. Assessing the social and environmental impacts of the just energy transition in Komati, Mpumalanga Province, South Africa. *Energy Res. Soc. Sci.* **2024**, *111*, 103489. [CrossRef]
56. Mo, Y.; Wang, H. Sustainability of Road Transportation in China. *Energies* **2023**, *16*.

57. Zhang, J. Energy Transitions and Political Economy: A Study on the THK Model. Master's Thesis, Leuphana University, Lüneburg, Germany, 2023.
58. Kaphengst, T.; Velten, E.K. *Energy Transition and Behavioural Change in Rural Areas—The Role of Energy Cooperatives*; WWWforEurope Working Paper: Vienna, Austria, 2014.
59. Edkins, A.; Geraldi, J.; Morris, P.; Smith, A. Exploring the front-end of project management. *Eng. Proj. Organ. J.* **2013**, *3*, 71–85. [CrossRef]
60. Ghanadan, R. *Understanding Energy Transitions in Southern Africa*; Stockholm Environment Institute: Stockholm, Sweden, 2020.
61. Jianu, A.; Jianu, L. Financial Risk and Infrastructure in Oil & Gas. *Energies* **2023**, *16*.
62. Merven, B.; Stone, A.; Moonsamy, V.; Caetano, T.; Ahjum, F.; Hartley, F. *Multi-Nodal Energy Systems Modelling: South Africa Scenarios*; Technical Report; UCT Energy Systems Research Group: Cape Town, South Africa, 2023.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.