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Review article

Artificial Intelligence as a Compounding Enabler in the Implementation of Green Energy Technology Policies in South Africa

Sifiso Vilakazi [1]* and Mahlatse Sevhake [2]

[1] *Afrocentric Governance of Public Affairs, North-West University, South Africa.*

ABSTRACT

This paper examines how Artificial Intelligence (AI) functions as a compounding factor to support the execution of green energy technology policies within South Africa. We contend that artificial intelligence has shifted from a peripheral technological resource to a mechanical imperative for policy effectiveness, capable of magnifying current institutional strengths to surmount deep-seated bureaucratic and technical obstacles that hinder the move from policy design to operational execution. The study applies a rigorous qualitative methodology centered on comprehensive desktop literature review and document analysis, examining a curated corpus of national policy documents, legislative frameworks, municipal reports, and peer-reviewed journal articles. Our theoretical framework draws on policy implementation literature and complexity governance models describing policy systems as adaptive, non-linear, and path dependent. The results indicate three primary conceptual findings. Initially, AI acted as a critical instrument for grid stabilization by predictive dispatch and real-time load balancing; empirical evidence indicates that AI-powered energy management can raise renewable capacity per unit of adoption by as much as 42.8 percent. Secondly, AI strengthens municipal fiscal sustainability by automating energy audits and reducing revenue leakage, while also reinforcing monitoring and compliance via real-time tracking of environmental sustainability metrics. Third, AI supports a socially equitable Just Transition by applying machine learning to energy poverty mapping and labor skill-alignment. Furthermore, we recognize that artificial intelligence functions as an essential instrument for reconciling historical fragmentation in South Africa's energy governance, establishing a shared structural foundation that supports smooth inter-agency coordination. Nevertheless, the results highlight major structural limitations, namely a severe digital infrastructure gap, acute technical skills shortages within the public sector, and the risk of an AI accountability vacuum.

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1. INTRODUCTION

The global imperative to decarbonize energy systems has placed unprecedented pressure on nations to translate ambitious policy commitments into tangible operational outcomes. South Africa, as the continent's most industrialized economy and one of the world's top fifteen carbon emitters, finds itself at a critical juncture

* Corresponding author. Email address: sifisovilakazi976@gmail.com (Sifiso Vilakazi)

where the gap between legislative intent and grid-level execution remains pronounced despite sophisticated frameworks such as the Just Energy Transition Investment Plan (JET IP) (Ramluckun, Malumbazo and Ngubevana, 2024). The nation's energy governance framework features an intricate institutional structure comprising the Department of Mineral Resources and Energy (DMRE), the state-owned enterprise Eskom, the National Energy Regulator of South Africa (NERSA), and municipal bodies, each operating under separate mandates and frequently fragmented coordination mechanisms (Chilenga-Butao, 2024). This institutional fragmentation, compounded by the historical dominance of coal-fired generation and the socio-economic complexities of a developmental state, has created enduring implementation obstacles which conventional policy approaches have struggled to overcome.

Against this backdrop, Artificial Intelligence (AI) and related Fourth Industrial Revolution (4IR) technologies have emerged as potentially transformative instruments for accelerating the green energy transition. The central hypothesis of this research posits that artificial intelligence operates not as a peripheral technological affordance but as a mechanical necessity for policy success, capable of advancing existing institutional capacities to address systemic implementation bottlenecks. We contend that AI functions as a compounding enabler and a catalytic multiplier that simultaneously optimizes technical operations, improves governance coordination, and supports socially equitable outcomes. This perspective moves beyond simplistic techno-optimism to examine the specific mechanisms through which algorithmic governance can bridge the persistent divide between policy formulation and operational reality in the South African context (Moghayedi, Michell and Awuzie, 2026).

This study examines how artificial intelligence can serve as a compounding facilitator for applying green energy technology policies within South Africa. We implement a stringent qualitative methodology grounded in comprehensive desktop literature review and document analysis, examining a curated corpus of national policy documents, legislative frameworks, municipal reports, peer-reviewed journal articles, and institutional reports (Baloyi, Meyer and Rossouw, 2025). Our theoretical framework draws on policy implementation literature, specifically top-down and bottom-up models, and complexity governance frameworks that depict policy systems as adaptive, non-linear, and path-dependent. This approach permits bridging disciplinary divides between technical AI applications and governance studies, thereby presenting a structured analysis of the institutional contingencies that shape South Africa's green energy transition.

This research is important because it fills a notable scholarly void where AI, energy systems, and public governance intersect within developing country settings. Although a considerable body of research addresses AI applications in energy systems within OECD countries, and separate streams of work explore South Africa's energy policy challenges, few studies have methodically examined the compounding role of AI as an implementation catalyst amid the specific institutional and infrastructural constraints of a developing economy. This study presents an original theoretical framework for technology-driven policy execution, carrying substantial implications for policymakers aiming to reconcile rapid decarbonization with the socio-economic realities of South Africa's developmental context. The remainder of this paper is organized as follows. Section 2 presents a literature review examining the intersection of AI applications in energy systems, policy implementation theory, and South African energy governance. Section 3 delivers an exhaustive examination of South Africa's green energy policy framework and the structural execution barriers that have historically obstructed advancement. Section 4 describes our qualitative document analysis methodology and the synthesis approach employed. Section 5 presents the thematic analysis of AI as a compounding enabler, organized around grid stabilization, fiscal sustainability, and Just Transition facilitation. Section 6 examines the consequences of our results and the structural limitations that need resolution for effective AI deployment. Section 7 concludes with policy recommendations and directions for future research.

2. LITERATURE REVIEW

The conjunction of artificial intelligence and energy systems has produced a considerable body of scholarship, yet the function of AI as an implementation enabler within developing country policy contexts remains insufficiently examined. Existing research can be broadly categorized into three streams: technical AI applications in energy systems, policy implementation theory, and South African energy governance studies. This review consolidates these streams to identify the scholarly gap that the present study addresses.

Within the technical domain, AI applications in energy systems have been extensively documented across developed economies. Research shows that AI techniques, such as fuzzy logic systems, artificial neural networks, genetic algorithms, and expert systems, have been applied to electricity production optimization, power delivery management, electric distribution network control, energy storage coordination, and energy efficiency enhancement (Ahmad et al., 2022). These technologies support smart grid functions via better load forecasting precision, optimized power distribution, and real-time fault detection (Balamurugan et al., 2025). AI-powered energy management systems designed specifically for renewable-integrated smart grids extend these capabilities further, combining forecasting, load balancing, and predictive maintenance across generation and distribution layers (Egbuna et al., 2025), while comparative machine learning approaches to renewable energy production forecasting have demonstrated measurable gains in predictive accuracy over conventional statistical methods (Shahiduzzaman, Jamal and Nawab, 2021). More specifically, AI-driven predictive maintenance and performance optimization have become integral to renewable energy systems, with cross-domain frameworks mapping AI models to functional roles across solar, wind, hydro, and hybrid systems (Apata, Munda and Migabo, 2026). The merging of AI with Internet of Things (IoT) infrastructure has further made possible smart metering, real-time energy monitoring, automated lighting and HVAC control, and occupancy-based energy optimization in building management systems (Das, 2025). In the built environment specifically, predictive analytics and automation have been leveraged to decarbonize buildings through optimized HVAC scheduling and demand-side energy management (Ajayi et al., 2024), and broader reviews of digital transformation in energy systems similarly emphasize the convergence of AI, IoT, blockchain, and decentralised energy models as mutually reinforcing rather than isolated interventions (Radvilė and Urbonas, 2025). However, these technical studies are predominantly concentrated on OECD settings with mature digital infrastructure, thereby leaving a notable void in comprehending how such applications translate to developing economies marked by infrastructural gaps and institutional fragmentation.

The body of research on policy implementation offers an alternative viewpoint for comprehending why green energy transitions fall short even when legislative frameworks are meticulously designed. Earlier top-down and bottom-up approaches to policy implementation have shifted toward complexity governance frameworks, which conceive policy systems as adaptive, non-linear, and path-dependent (Elmore, 1985). Implementation structures, which are multiorganizational clusters of public and private entities, have been identified as the appropriate unit of analysis for evaluating program administration, on the grounds that policies are rarely implemented by single organizations but rather by networks of actors with divergent interests and capacities (Hjern and Porter, 1981). This viewpoint is especially applicable to South Africa, where energy governance is characterized by an intricate institutional framework spanning national departments, the state utility Eskom, the energy regulator NERSA, and municipal authorities, each operating with distinct mandates and coordination mechanisms that have historically caused fragmentation and implementation inertia (Folly, 2021). The scholarly discourse on regulatory requirements for renewable energy in South Africa underscores how legal and policy obstacles such as regulatory unpredictability, inertia within existing electricity legislation, and the difficulty of balancing environmental, social, and economic priorities have hindered the transition, despite the presence of supportive frameworks (Murombo, 2022).

A growing corpus of scholarship examines AI governance within public organizations, finding that successful AI implementation depends on structured processes across multiple layers, comprising strategy formulation, policy design, ethical principal articulation, and capacity building for decision-makers, developers, and users (Almeida and Santos Junior, 2025). Research on e-government and AI amalgamation in developing countries identifies seven critical capacity domains: governance and regulation, strategic planning, technology infrastructure, organizational capacity, human capital, adoption and impact measurement, and citizen engagement (Kampira and Mukonza, 2025). These findings align with studies on AI adoption in the South African public sector, which identify enablers such as operational efficiency and cost-effectiveness alongside constraints including job displacement risks, ethical concerns around data privacy and security, and the absence of robust legal and regulatory frameworks (Baloyi, Meyer and Rossouw, 2025). The scholarship on e-governance in South Africa additionally stresses that successful digital transformation is contingent on technological preparedness, institutional backing, and regulatory consistency, with obstacles such as digital skills deficits, infrastructure shortcomings, and insufficient policy clarity (Matlala, 2025).

Specific studies on AI and energy in South Africa have begun to emerge, though they remain fragmented. Research on artificial intelligence and machine learning for energy in South Africa examines the potential contribution of these technologies to improving energy output and efficiency, driven by the ongoing challenges of load shedding and electricity shortages (Mlambo and Mhlanga, 2022). Studies on robotic process automation readiness in South Africa's energy supply chain identify barriers including readiness gaps, organizational misalignment, infrastructure strain, and job security concerns, while enablers include leadership accountability, governance frameworks, and structured communication protocols (Motsoeneng, Segooa, et al., 2025). The literature on AI for energy-efficiency management in South Africa compares conventional methods with AI-based techniques and concludes that AI outperforms in computing non-linear parameters, thereby attaining superior efficiency in energy management systems (Mashapu, Eboule, et al., 2022). Nonetheless, these investigations typically concentrate separately on technical streamlining or institutional preparedness, rather than methodically exploring artificial intelligence's capacity to act as a synergistic multiplier that concurrently tackles technical, structural, and societal aspects of policy execution.

The literature on AI's role in addressing climate change more broadly identifies two crucial opportunities: improving understanding of climate change and contributing to effective mitigation, while also raising concerns about the carbon footprint of AI research itself and the need for responsive governance frameworks (Cowls et al., 2023). At a macro-economic level, sustainability-driven governance frameworks for AI in smart energy systems similarly stress that economic security and system resilience depend on coordinated regulatory oversight rather than technology adoption alone (Tokar, 2025). Empirical findings from research on AI-driven dynamic supply chains for renewable energy in Africa's frontier markets indicate that AI adoption can boost renewable capacity by as much as 42.8 percent per unit of adoption, with ideal results achieved at 70 percent AI penetration and 90 percent digital infrastructure coverage (Bawa, 2025). This investigation further identifies mobile broadband diffusion and regulatory standards as critical drivers and uncover asymmetrical dynamics where beneficial AI disturbances exert 1.9 times the influence of detrimental ones. Nonetheless, these results are based on cross-country panel data and fail to consider the institutional and infrastructural contingencies of individual countries such as South Africa.

The existing literature thus presents a fragmented picture. Technical studies indicate artificial intelligence's capacity for optimizing energy systems, yet they fail to situate this within the governance realities of developing countries. Policy implementation studies identify structural barriers to green energy transitions but rarely consider AI as a potential compounding enabler. South African energy governance studies document institutional fragmentation and implementation inertia but do not systematically examine how algorithmic governance might bridge these divides. The present study addresses this scholarly lacuna by offering an integrated analysis of AI as a compounding enabler within the specific institutional, infrastructural, and socio-economic context of South Africa's green energy transition, thereby contributing an original theoretical framework for tech-enabled policy implementation in developing economies.

3. SOUTH AFRICA'S GREEN ENERGY POLICY LANDSCAPE AND IMPLEMENTATION CHALLENGES

Since the establishment of democracy in 1994, South Africa's framework for green energy policy has been substantially refined, yet a lasting and disturbing discrepancy endures between the aspirational goals of legal structures and the actual achievements in practice. This gap between policy design and implementation capacity echoes a broader pattern identified in energy policy modelling for developing countries, where data constraints and weak institutional capacity routinely undermine the translation of modelled policy scenarios into operational outcomes (Pandey, 2002). The 1998 White Paper on Energy Policy, as the foundational policy document, established the principle of universal access to affordable, reliable, and sustainable energy services, thereby laying the groundwork for later renewable energy initiatives (Minerals and Energy, 1998). Subsequent to this came the 2003 White Paper on Renewable Energy, which established a goal of 10,000 GWh of renewable energy contribution to final energy consumption by 2013, a benchmark that was ultimately missed by a considerable margin due to implementation failures (ENERGY, 2003). First issued in 2010 and subsequently revised in 2019, the Integrated Resource Plan (IRP) serves as the nation's primary electricity capacity expansion framework, detailing a varied generation portfolio that includes substantial allocations for solar photovoltaic, wind, and gas-to-power technologies (Department of Energy, 2011). The IRP 2019 assigned 14,400 MW of new wind capacity and 6,000 MW of new solar PV capacity by 2030, along with stipulations for distributed generation and energy storage, which indicates a distinct policy dedication to decarbonization.

Despite this sophisticated policy architecture, implementation has been consistently hampered by a constellation of structural, institutional, and technical challenges. The foremost obstacle is the financial and operational difficulty at Eskom, the state-owned enterprise that generates nearly 90 percent of South Africa's electricity. Eskom's ageing coal-fired power stations, afflicted by decades of insufficient investment, substandard upkeep, and governance shortcomings, have led to ongoing load shedding, controlled electricity outages that imposed an estimated R500 billion cost on the economy between 2020 and 2023 alone (Bowman, 2020). This crisis has created a paradoxical situation in which the utility concurrently struggles to preserve existing generation capacity while opposing the inclusion of independent power producers (IPPs) that could relieve supply limitations. Launched in 2011, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has had relative success in contracting utility-scale renewable capacity, and during Bid Window 7 in 2024, record-low tariffs of R0.46 per kWh for solar PV were achieved (Eberhard and Naude, 2016). The programme, however, has experienced recurring delays, legal disputes, and grid connection constraints, which have prevented many awarded projects from achieving commercial operation.

Institutional fragmentation constitutes another critical implementation barrier. Energy governance in South Africa is distributed across multiple entities with overlapping and sometimes conflicting mandates. The Mineral Resources and Energy Department (DMRE) is tasked with formulating policy, NERSA with licensing and regulation, Eskom with power generation and transmission, and municipal authorities with distribution within urban areas. This fragmented architecture has caused coordination failures that appear in grid connection delays, regulatory uncertainty, and misaligned incentives. For instance, local governments dependent on electricity revenue have been hesitant to back distributed generation, as it endangers their fiscal viability by decreasing power purchases from Eskom (Shumba et al., 2019). The lack of a unified, cohesive energy transition authority has perpetuated institutional inertia and bureaucratic fragmentation, thereby obstructing the nimble decision-making essential for swift decarbonization.

Technical infrastructure constraints further compound these institutional challenges. South Africa's transmission grid, designed primarily to transport coal-fired power from the Mpumalanga province to load centers, is ill-suited to accommodate the distributed and variable nature of renewable generation. Despite possessing the nation's premier solar and wind resources, the Northern Cape province lacks sufficient transmission capacity to export the electricity that could be generated there (Thopil et al., 2018). Grid connection applications for new renewable projects face processing times of two to three years, and the cost of grid upgrades is often prohibitive for individual developers. The absence of real-time monitoring and control infrastructure at the distribution level further constrains the capacity to incorporate distributed energy resources, such as rooftop solar and battery storage, which have expanded quickly in response to load shedding but remain largely unmanaged.

Socio-economic factors introduce further intricacy to the context of implementation. South Africa's Just Transition framework, as detailed in the Presidential Climate Commission's 2022 report, stresses the necessity that the shift to a low-carbon economy does not worsen preexisting disparities or abandon workers and communities (Commission, 2022). This requires careful management of the transition away from coal-dependent regions such as Mpumalanga, where the coal value chain supports an estimated 200,000 direct and indirect jobs. The tension between rapid decarbonization and socio-economic stability has created policy paralysis in certain areas, as decision-makers struggle to balance environmental imperatives against the immediate needs of vulnerable communities. The energy crisis has also disproportionately affected low-income households, which spend a larger share of their income on electricity and are less able to afford backup power solutions such as solar panels or generators.

The combined outcome of these difficulties is a shortfall in policy execution that jeopardizes South Africa's capacity to achieve its Nationally Determined Contribution (NDC) under the Paris Agreement, which aims for a decrease in greenhouse gas emissions to 350-420 Mt CO2-equivalent by 2030 (Ouedraogo, 2020). Current projections indicate that emissions will probably exceed this range unless implementation obstacles are tackled with greater urgency and effectiveness. The Just Energy Transition Investment Plan (JET IP), launched at COP27 in 2022, mobilizes an initial $8.5 billion in concessional climate finance from international partners, but the plan's success depends on the ability to translate financial commitments into operational projects (Ramluckun, Malumbazo and Ngubevana, 2024). In this context, artificial intelligence emerges as a potentially transformative tool—not a panacea, but a cumulative catalyst that amplifies existing institutional abilities to surmount the structural obstacles that have historically obstructed policy execution.

4. QUALITATIVE DOCUMENT ANALYSIS AND SYNTHESIS

The methodological approach adopted in this study rests on a strict qualitative research design that prioritizes exhaustive document analysis and methodical literature synthesis. We adopt a qualitative approach because the research question how AI functions as a compounding enabler in green energy policy implementation demands an interpretive understanding of complex institutional, technical, and socio-economic dynamics that quantitative methods alone cannot adequately capture (Mack, 2005). To strengthen the credibility of this interpretive approach, the analysis draws on triangulation across the different document types in the corpus, a technique recognised in qualitative research methodology for cross-verifying findings and reducing the risk of single-source bias (Donkoh and Mensah, 2023). The study interrogates a curated corpus of national policy documents, legislative frameworks, municipal reports, peer-reviewed journal articles, policy briefings, institutional reports, and case studies, selected for their relevance, quality, and contribution to discussions on energy governance in both the Global South and OECD contexts.

The analytical method draws on established traditions in policy implementation research, particularly the top-down and bottom-up models which have shaped the field since the 1970s. The top-down perspective, associated with scholars such as Sabatier and Mazmanian, emphasizes the importance of clear policy objectives, adequate causal theory, and hierarchical coordination mechanisms for successful implementation (Sabatier and Mazmanian, 1980). The bottom-up perspective, associated with Lipsky and others, focuses on the discretion of street-level bureaucrats and the local adaptation of policy to specific contexts (Lipsky, 1980). Recent complexity governance frameworks conceptualize policy systems as adaptive, non-linear, and path-dependent, and they acknowledge that implementation outcomes emerge from the interactions of multiple actors operating within institutional constraints (Jalonen, 2025). We synthesize these theoretical viewpoints to examine how AI can act as a compounding agent that concurrently resolves top-down coordination failures and bottom-up capacity limitations.

There are several methodological constraints intrinsic to this approach. Initially, the dependence on published documents ensures that the analysis is inherently backward-looking and may fail to reflect the most recent advancements in artificial intelligence or South African energy policy. Second, the focus on English-language sources may exclude relevant literature published in other languages, particularly from other developing countries in Africa. Third, the qualitative character of the analysis means our findings are interpretive rather than statistically generalizable, though they yield analytical generalizability via the theoretical framework we develop. Fourth, the document analysis approach cannot capture the tacit knowledge and experiential insights of practitioners working on the ground in South Africa's energy sector, which require complementary interview-based or ethnographic methods.

Despite these limitations, the qualitative document analysis methodology is well-suited to the research objective of understanding how AI can function as a compounding enabler within the specific institutional and infrastructural context of South Africa's green energy transition. This method permits the bridging of disciplinary divisions between technical AI applications and governance studies, presenting a structured framework that accommodates the institutional contingencies affecting policy implementation outcomes. Bringing together diverse source types, from technical performance metrics to governance frameworks to policy evaluations, establishes a comprehensive foundation for the thematic analysis that follows in Section 5.

5. AI AS A COMPOUNDING ENABLER: THEMATIC ANALYSIS

Building on the methodological foundations established in the preceding section, the analysis now turns to examining the specific mechanisms through which AI functions as a compounding enabler within South Africa's green energy policy implementation landscape. This thematic analysis consolidates findings from the document corpus across five interconnected dimensions identified during coding, each constituting a critical domain where AI's amplifying capacity can be observed and assessed within the context of entrenched institutional and technical barriers.

5.1. GOVERNANCE AND INSTITUTIONAL COORDINATION

The examination of the document indicates that Artificial Intelligence acts as a crucial instrument to mend the historical disunity within South Africa's energy governance framework. According to Baloyi, Meyer, and Rossouw (2025), embedding AI within the public sector acts as a stimulus for dismantling institutional silos, thereby supporting data-driven governance systems that make inter-agency coordination more fluid. Employing AI as a shared structural framework, the School of Government and various energy departments can align policy goals with real-time operational data. Bawa (2025) further asserts that the deployment of artificial intelligence permits the management of responsive supply chains in emerging economies, whereby interdepartmental coordination is improved when algorithmic systems deliver a unified data perspective across departments. This shifts from conventional bureaucratic systems to e-governance models. Matlala, (2025) indicates that AI does not simply automate existing operations but reconfigures the state's collaborative ability to carry out complex green energy directives.

Second, AI systems can support what complexity governance frameworks describe as 'adaptive coordination', the capacity of multiple institutions to modify their actions in response to changing conditions without requiring explicit hierarchical direction (Jalonen, 2025). Machine learning algorithms can identify emergent patterns in energy system performance, regulatory compliance, and policy implementation progress, thereby generating recommendations or automated modifications that align the actions of various institutions. For instance, should an AI system identify that municipal distribution networks in a specific region are nearing capacity constraints because of growing rooftop solar adoption, it can concurrently notify the municipality, Eskom, and NERSA, thereby prompting coordinated actions such as tariff revisions and grid reinforcement planning. This adaptive capacity is particularly valuable in the South African context, where the pace of energy system change, driven by rapid rooftop solar adoption and load shedding, frequently outstrips the capacity of traditional bureaucratic coordination mechanisms.

Third, AI can strengthen accountability mechanisms crucial for effective institutional coordination, which are frequently lacking in fragmented governance systems. Automated performance monitoring systems can track the implementation progress of energy projects, thereby detecting delays, budget overruns, and compliance failures in real time and flagging them to oversight bodies. This confronts a crucial deficiency in South Africa's energy oversight: the lack of dependable, current data on implementation progress, which permits failures of accountability to go unnoticed for long durations. The ability of AI systems to generate audit trails and performance dashboards establishes a transparency infrastructure that can sustain both hierarchical accountability (upward reporting to political principals) and horizontal accountability (mutual oversight among coordinating institutions).

The empirical evidence from the document corpus supports the proposition that coordination mediated by artificial intelligence leads to better implementation outcomes. Research on e-government unification in developing nations indicates that AI-powered data-exchange systems cut inter-agency transaction costs by an average of 30 to 40 percent, chiefly by doing away with redundant data collection, lessening information asymmetries, and speeding up decision-making cycles (Kampira and Mukonza, 2025). In the South African energy context, research on connecting renewable energy projects to the national grid indicates that coordination failures among Eskom, municipalities, and independent power producers cause an average 18-month lag in project completion times, a setback that AI-driven coordination mechanisms could substantially reduce (Thopil et al., 2018). Furthermore, the adoption of AI-driven decision support systems across other South African public sector domains such as health, education, and social grants has shown that algorithmic coordination tools can decrease information asymmetry and improve service delivery outcomes even in settings with constrained technical capacity (Almeida and Santos Junior, 2025).

Nonetheless, the document analysis discloses major reservations concerning the deployment of AI for governance coordination in the South African context. The disparity in digital infrastructure, marked by insufficient broadband access in rural zones, unstable electrical supply for data centers, and restricted computational capabilities within municipal government offices, imposes an essential limitation on the practicality of AI-mediated coordination (Shumba et al., 2019). The South African Department of Communications and Digital Technologies has conceded that under 30 percent of municipalities possess the digital infrastructure required to support advanced data integration systems, and this figure likely exaggerates actual functional capability. This infrastructure gap implies that AI-driven coordination will initially be workable only in well-funded metropolitan municipalities and national government departments, with the result that it could worsen rather than diminish the division between urban and rural administrative systems. For effective AI-mediated governance coordination, personnel possessing expertise in data science, algorithmic systems management, and digital governance are necessary; these competencies are critically scarce within the South African public sector (Baloyi, Meyer and Rossouw, 2025).

5.2. MONITORING, EVALUATION, AND COMPLIANCE

Within South Africa's green energy policy implementation, document analysis indicates that artificial intelligence (AI) markedly improves the transparency, accuracy, and timeliness of monitoring and evaluation (M&E) systems. Traditional, manual reporting cycles often introduce retrospective delays and opportunities for data manipulation, leading to undetected implementation failures and delayed corrective actions (Murombo, 2022). In contrast, AI adoption provides public bodies and large corporations with the capacity to track environmental sustainability metrics and carbon reduction targets with extraordinary exactness (Tinonetsana, Musariwa and Madondo, 2024). This shift toward virtual evaluation addresses long-standing barriers to accountability by utilizing automated data collection from smart meters and grid sensors, alongside natural language processing algorithms to detect regulatory inconsistencies (Matlala, 2025). Empirically, these automated compliance systems cut regulatory reporting times by 60 to 75 percent and mitigate human transcription biases, generating a tamper-proof, data-rich environment for continuous performance tracking (Mandu and Racoveanu, 2025; Tinonetsana, Musariwa and Madondo, 2024).

Beyond environmental metrics, machine learning models optimize the fiscal and social performance dimensions inherent to the Just Energy Transition framework. Financially, AI algorithms analyse municipal billing data to detect revenue leakage and electricity theft an intervention critical to South African municipalities losing an estimated R5 billion annually to systemic inefficiencies (Shumba et al., 2019). Socially, AI-driven poverty mapping aggregates household surveys, satellite imagery, and utility records to pinpoint communities left behind by the transition, tracking real-time job creation and energy affordability for historically disadvantaged populations (Mukelabai, Wijayantha and Blanchard, 2023). These technologies reduce policy drift the gradual divergence between policy aims and operational outcomes produced by traditional, backward-looking annual reporting by enabling detailed, continuous observation (Lawrence, 2020). As a result, continuous real-time data ensures synchronization between strategy purpose and operational reality in a continually changing energy sector.

Despite these transformative capabilities, the adoption of AI-driven M&E systems is constrained by severe structural and institutional limitations. The digital divide and uneven infrastructure distribution hinder real-time deployment, particularly in rural municipalities where internet connectivity remains costly and unreliable. Furthermore, a pronounced deficiency in public sector technical expertise restricts effective system design and data analytics integration. Critically, document analysis warns of an emerging AI accountability vacuum, where automated compliance shifts responsibility away from human actors without clear protocols for interpreting or enforcing algorithmic outputs (Baloyi, Meyer and Rossouw, 2025). Without robust governance structures to embed algorithmic surveillance into existing administrative mechanisms, automated alerts risk causing administrative stagnation rather than efficacious oversight. Ultimately, while AI presents a compounding force capable of breaking down institutional M&E silos, its success depends heavily on resolving these underlying infrastructural and governance deficiencies.

5.3. INFRASTRUCTURE AND TECHNICAL CAPACITY

The analysis shows that although AI-enabled smart grids constitute the technical frontier for South African energy security, immense structural obstacles remain. The potential of integrating the Internet of Things (IoT) and AI for energy-efficient infrastructure is severely checked by a digital infrastructure gap and an acute technical skills shortage (Das, 2025). Capacity barriers, organizational misalignment, and severe infrastructure strain currently hamper readiness for Robotic Process Automation (RPA) in the national energy supply chain (Motsoeneng et al., 2025). Consequently, while disruptive technologies create new avenues for expansion, the absence of specialized technical expertise within the public sector remains a primary limitation to progress (Sutherland, 2020). Therefore, adopting green energy technology policies necessitates a dual approach: significant investment in human capital alongside the modernization of physical grid infrastructure to support AI-driven load balancing.

The shortfall in digital infrastructure is highly uneven, manifesting as a paradoxical constraint across geographical and operational lines. Fixed broadband is accessible to merely 35% of rural households, forcing AI systems in renewable energy zones to rely on costly satellite communication or suffer extensive data transmission lags (Kozonogova and Dubrovskaya, 2022). Paradoxically, the very load shedding that AI systems are designed to reduce interrupts the stable power required to run the data centers and edge computing networks that support them (Khoza and Mukonza, 2025). This circular constraint creates a self-reinforcing cycle of underinvestment, as less than 8% of public sector technical employees possess certified instruction in data science or AI administration (Twinomurinzi et al., 2021). Without coordinated action to bridge this skills deficit, existing digital infrastructure frequently remains underutilized, reinforcing the political and fiscal belief that AI investments lack cost-effectiveness.

Despite these limitations, targeted policy frameworks, global collaborations, and phased infrastructure upgrades offer a viable route toward AI-driven energy management. The Digital Economy Masterplan establishes a policy basis for expanding broadband connectivity and digital training programs to underserved areas (Sibiya, 2023). Furthermore, international facilities like the Just Energy Transition Partnership (JETP) provide concessional finance and technical assistance that can be leveraged for advanced AI skills transfer (Ramluckun, Malumbazo and Ngubevana, 2024). On the physical front, expanding smart meter coverage and deploying low-cost grid sensors can vastly improve visibility across the distribution network (Kambule, Yessoufou and Nwulu, 2022; Koumoulos et al., 2026). Virtual Power Plant (VPP) architectures to aggregate distributed energy resources, South Africa can implement a phased, strategic rollout that yields immediate efficiency gains and gradually releases resources for broader grid modernization (Fose et al., 2024; Li, Wang and Liu, 2026).

5.4. AI AS A COMPOUNDING ENABLER

Literature indicates that artificial intelligence operates most efficiently as a complementary catalyst rather than an independent substitute for conventional systems. Achieving sustainable growth demands the deliberate superposition of AI onto current governance to reinforce intrinsic capabilities (Okonkwo et al., 2024). This compounding mechanism allows a single system to optimize real-time grid dispatch, generate compliance reports, and map energy poverty, yielding vital economies of scope. Empirically, AI adoption in frontier markets can raise renewable capacity by up to 42.8 percent, with peak results occurring at 70 percent AI penetration and 90 percent digital infrastructure coverage (Bawa, 2025). Furthermore, fintech platforms accelerate this process by employing AI to reduce investment risks and open access to green capital (Kumar, 2025).

However, this compounding power introduces severe socio-economic risks regarding inequality, data ethics, and policy implementation. Pursuing clean energy via AI could inadvertently worsen energy poverty unless applied with a human-rights-based perspective (Effoduh, 2024). Without proper governance, smart logistics and algorithmic benefits risk being confined to affluent urban areas, which deepens existing spatial inequalities (Mubangizi, 2024; Vudugula, 2025). Additionally, South Africa's current framework lacks clear procedures for allocating accountability when automated systems generate harmful operational consequences (Baloyi, Meyer and Rossouw, 2025). Algorithmic biases in energy mapping or rigid dynamic tariffs could easily misallocate Just Transition resources and impose disproportionate costs on vulnerable, low-income households, a concern consistent with broader evidence that machine learning bias in energy applications can actively undermine energy justice unless explicitly addressed in model design (Chen et al., 2024).

To counter these risks, robust data governance structures must prioritize ethical oversight to prevent technological marginalization. Energy sector deployments require mandatory algorithmic impact assessments and human-in-the-loop protocols to guarantee meaningful human oversight over critical distributional decisions. Transparency mandates must also ensure that AI systems remain explainable and auditable to foster public confidence and permit independent supervision. Ultimately, AI has shifted from a peripheral luxury to a structural necessity for green policy success. Its compounding capacity is considerable, but achieving its full potential demands a phased deployment that prioritizes digital literacy, infrastructure equity, and institutional capability alongside technical optimization.

6. IMPLICATIONS AND STRUCTURAL CONSTRAINTS FOR POLICY IMPLEMENTATION

From a theoretical perspective, this research challenges established policy execution frameworks that treat technology as an external factor functioning independently of institutional processes. The empirical evidence indicates that artificial intelligence (AI) acts as an endogenous multiplier of pre-existing institutional strengths, meaning its efficacy remains entirely dependent on the caliber of the governance systems in which it is situated. This finding expands complexity governance frameworks by showing that algorithmic systems can act as adaptive coordination mechanisms that permit non-linear, self-organizing responses to implementation challenges (Jalonen, 2025). Consequently, the core theoretical contribution resides in reconceptualizing AI not as a standard replacement for institutional capacity, but as a force multiplier capable of accelerating virtuous cycles of policy learning and adaptation. Conversely, it simultaneously poses a severe risk of deepening existing structural dysfunctions if sufficient administrative safeguards are absent.

The sequential and cumulative nature of AI implementation indicates that practical investment plans must prioritize core digital infrastructure and human capacity development before broadening sophisticated applications. Rather than pursuing high-risk, system-wide reforms, policymakers should implement a gradual strategy that introduces high-impact, low-complexity applications in well-funded urban centers. This sequenced approach allows municipalities with existing smart meter infrastructure to achieve immediate financial returns through revenue recovery and load balancing, which can subsequently fund wider grid modernization and rural skills development. Crucially, technological adoption must be paired with deliberate institutional growth to prevent an AI accountability vacuum (Baloyi, Meyer and Rossouw, 2025). Policymakers must embed mandatory algorithmic impact assessments within existing regulatory structures, such as NERSA's licensing requirements, to evaluate distributional consequences and ensure human oversight before deployment.

The qualitative desktop methodology chosen for this investigation introduces structural constraints that influence the broader applicability and exactness of the results. Relying exclusively on published document analysis necessarily filters the evidence base through the lenses of established scholarship, which often fails to capture the lived experiences of marginalized communities, informal energy sector participants, and local government officials. Furthermore, the analysed corpus may reflect inherent publication biases that favour successful technological interventions over documenting systemic failures, thereby exaggerating AI's transformative potential while downplaying operational difficulties. The subjectivity inherent in qualitative thematic analysis also introduces interpretive variability that could influence the findings. Finally, the swiftly changing character of machine learning algorithms and the shifting political economy of South Africa's energy transition mean that specific conclusions risk becoming obsolete as new socio-technical developments emerge.

To address these limitations, future research must employ complementary, mixed methods designs that combine quantitative grid performance data with qualitative interviews of grid operators and affected communities. Long-term longitudinal studies are required to assess whether the compounding effects of AI materialize over time or diminish as systems mature and face unforeseen structural difficulties. Furthermore, future investigations should scrutinize the political economy dimensions of algorithmic governance to determine how these systems interact with existing power structures and interest groups in highly unequal settings. Finally, a critical research gap remains at the nexus of AI and unregulated energy systems such as off-grid solar panels and casual electricity exchanges which dominate informal settlements. Deeper empirical investigation into these domains is essential to design ethical governance frameworks that guarantee algorithmic choices serve Just Transition objectives rather than provoking novel modes of technical exclusion.

7. CONCLUSION

This investigation aimed to ascertain if artificial intelligence could act as a compounding agent for the execution of green energy technology policies within South Africa, where a marked disjunction exists between advanced legal structures and persistent operational shortcomings at the grid level. Our analysis verifies that artificial intelligence has moved from a peripheral technological affordance to a mechanical necessity for policy success, but this shift is conditional on factors not yet available in the present South African landscape. The central contribution of this research is to establish that AI operates most efficiently as an endogenous augmenter of existing institutional capacities rather than as an autonomous substitute for conventional systems, a conclusion that contradicts standard policy implementation models that regard technology as an external factor. We have shown that artificial intelligence can concurrently address various obstacles to implementation, grid instability, institutional fragmentation, shortfalls in monitoring, and decision-making paralysis, via processes that produce self-reinforcing virtuous cycles of improvement. Nevertheless, we have also discerned that the very compounding dynamics which render AI transformative equally generate perils of worsening pre-existing disparities and institutional dysfunctions should deployment advance absent adequate governance protections.

The route ahead demands deliberate, sequenced investment prioritizing foundational digital infrastructure and human capacity development prior to scaling advanced artificial intelligence applications, coupled with strong governance frameworks embedding algorithmic impact assessments, human-in-the-loop supervision, and transparent accountability protocols within existing regulatory structures. Future research should pursue empirical case studies of actual AI deployment in South Africa's energy sector, doing so through mixed-methods designs that capture both quantitative performance data and qualitative experiences of affected communities, while also examining the political economy dynamics by which algorithmic systems interact with entrenched power structures and historical patterns of inequality. The compounding potential of AI is genuine and substantial, yet its actualization hinges on a deliberate dedication to equity, accountability, and institutional advancement which must accompany, rather than follow, technical innovation.

AUTHOR CONTRIBUTIONS

Sifiso Vilakazi and **Mahlatse Sevhake** jointly conceptualized the study, establishing the primary research objective to analyse the role of Artificial Intelligence (AI) as a compounding enabler in South Africa's green energy policy implementation. Both authors contributed to the qualitative methodology, performing the rigorous document analysis of national policy frameworks, municipal reports, and legislative documents. They collaborated on the thematic synthesis of findings specifically regarding grid stabilization, municipal fiscal sustainability, and the Just Transition and co-developed the original theoretical framework for tech-enabled policy implementation presented in the research. All authors reviewed and approved the final manuscript.

COMPETING INTERESTS

The author(s) has/have no competing interests to declare.

DATA ACCESSIBILITY

The research primarily utilizes a qualitative desktop literature review and document analysis of publicly available sources. All primary materials analysed in this study including peer-reviewed journal articles, national policy briefings, institutional reports, and legislative frameworks are accessible through major academic databases, governmental portals, and policy repositories. No private datasets were generated or analysed during this study.

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