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Paving the Way for Sustainability: Can Green Infrastructure Drive Energy Efficiency in South Africa?

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Abstract

The persistent energy inefficiency in South Africa, driven by inconsistent renewable energy policies, weak institutional frameworks, and environmental degradation, thus underscores the dire need for an exhaustive evaluation of green infrastructure development. This paper explores the relationship between green infrastructure and energy efficiency between 2000 and 2023, using the energy ladder theory to analyze how the quality of institutions moderates such a relationship, which was analyzed by the Prais-Winsten estimation method. Major findings reveal that renewable energy generation and hydropower contribute to a significant reduction in carbon emission intensity and primary energy consumption, while forest cover and waste management contribute to improved energy efficiency. In fact, the institutional quality turns out to be a crucial moderator, reinforcing the positive impacts of green infrastructure, mainly renewable energy investment and hydropower development. The Granger causality test also presents a two-way complicated relationship between energy intensity and green energy investments, suggesting the interaction of energy efficiency policy. The study ends with the suggestion that reforms in institutional setup are a must to capture the environmental and economic potential of green infrastructure. Embedding policies of renewable energy expansion within a package of governance reforms is key to driving sustainable energy development in South Africa.

Keywords: *Sustainability, Green Infrastructural Development, Energy Efficiency, Prais-Winsten, South Africa.*
Jel Classification: Q56, Q42, O11, N77

Introduction

Green infrastructural development and energy efficiency are the two interlinked pillars for sustainable economic progress in the 21st century. Green infrastructure involves renewable systems, eco-friendly buildings, and sustainable urban planning, responding to critical challenges linked to environmental degradation and energy resource depletion (Khoshnava et al. 2020; Latasa et al., 2021). Energy efficiency, on the other hand, deals with the judicious use of energy resources for achieving maximum output and is a basic requirement for greenhouse gas emission reduction, cost minimization, and energy security (Liu et al., 2021). If taken in the context of South Africa, this interplay becomes much more pertinent because of its dual burden of economic dependence on energy-intensive industries and concurrent vulnerability to climate change.

Notwithstanding, South Africa remains one of the most energy-intensive economies in the world, with about 85% of its electricity needs being supplied by coal-fired power stations, making it the biggest greenhouse gas emitter on the African continent (Ofori et al., 2022; World Bank, 2023). However, despite its contribution of more than 27% of sub-Saharan Africa's GDP, the country is plagued with severe inefficiencies in the use of energy (Onaran & Oyvat, 2024). The global share was roughly 28% of total energy investments in 2022, with renewable energy investment reaching over $500 billion a year (IEA, 2023). Energy intensity, a measure of energy consumption per unit of GDP, remains disproportionately high at 7.5 megajoules/dollar against the world average of 4.5 megajoules/dollar (World Bank, 2023). Transmission and distribution losses exceed 8% of total electricity production, more than double the OECD average, highlighting critical infrastructural deficits (Joseph & Inambao, 2021). These inefficiencies have far-reaching ramifications: economic stagnation, rising energy costs, and increased environmental damage. As such, energy efficiency remains one of the highest national priorities.

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However, green infrastructural development can offer a pathway to these challenges through the transformation of energy systems by the deployment of renewable energies, modernization of electricity grids, and eco-innovative urban design. To date, investments in solar, wind, and other renewable energy sources under the Renewable Energy Independent Power Producer Procurement Programme have added more than 8 gigawatts of renewable capacity to the national grid (Castro & Carvalho, 2023; Onaran & Oyvat, 2024). Yet, this constitutes less than 10% of South Africa's energy mix, while there is a lot that remains between the target and actual outcomes of policies (Nassani et al., 2023). In addition, the lack of integration between renewable energy infrastructure and existing coal-dominated grids undermines efforts toward energy efficiency. Although the National Development Plan and the Integrated Resource Plan articulate ways to make the economy less carbon-dependent, poor policy coordination, financial constraints, and inefficiencies in governance remain major obstacles (Castro & Carvalho, 2023).

The interaction that exists in a symbiotic relationship between green infrastructural development and energy efficiency lies at the heart of South Africa's transition to a sustainable energy future. Green infrastructure initiatives, if effectively implemented, reduce energy intensity and transmission losses while fostering economic resilience (Jacobs et al., 2021). On the reverse side, the accomplishment of energy efficiency provides the platform that can further attract more investments in green infrastructure, ensuring cost savings, reduced reliance on fossil fuels, and innovation in energy technologies (Pandey, 2020). However, the trend so far created indicates that South Africa has yet to take full advantage of this relationship. The lingering load shedding, costing an estimated R500 million per day per stage (Council for Scientific and Industrial Research, 2023), depicts high stakes of inefficiency, coupled with underutilization of renewable energy resources.

These challenges, in fact, require a paradigm shift in prioritizing and integrating green infrastructure and energy efficiency within South Africa's development agenda. Previous related studies have focused mainly on either technological solutions or the financial viability of a renewable energy project (Khoshnava et al., 2020; Latasa et al., 2021; Selim & Saeed, 2021; Liu et al., 2021). Analysis, though, rarely covers how green infrastructure systematically affects or is affected by energy efficiency (Essex & de Groot, 2019; Ofori et al., 2022; Onaran & Oyvat, 2024), particularly in South Africa. This paper bridges this critical gap by providing a comprehensive and data-driven analysis of how green infrastructure drives energy efficiency in South Africa while identifying barriers and opportunities to align policy and practice.

The paper consists of five sections. Following this introduction, the review of the related literature discusses the conceptual frameworks and empirical studies. The methodology outlines data, theoretical framework, model specification, and estimation techniques. Results and discussions present the analysis of empirical findings, while the conclusion gives the policy recommendations to foster green infrastructural development.

Literature Review

It is essential to achieve sustainable development through a synergistic integration of green infrastructure and energy efficiency, especially in countries like South Africa, where energy challenges, environmental concerns, and socio-economic inequalities are still persistent. This review synthesizes empirical insights on the intersection of green infrastructure development and energy efficiency, focusing on the South African context through a multi-dimensional analytical lens.

Green infrastructure involves strategically planned networks of natural and semi-natural features designed to provide essential ecosystem services such as energy conservation and climate regulation (Khoshnava et al., 2020). Key drivers like affordability, energy efficiency, and air quality are critical, as affordable green technologies can alleviate energy poverty in South Africa. Resource-efficient policies balancing cost-effectiveness with sustainability objectives are crucial for mitigating socio-economic disparities and enhancing eco-environmental resilience. The spatial distribution of green infrastructure within urban environments has a direct impact on energy efficiency and socio-economic equity. Using GIS-based spatial analysis in Pamplona, Spain, Latasa et al. (2021) show that uneven urban greening increases spatial

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inequalities, a finding that is quite applicable to the historically marginalized urban regions of South Africa. Such nature-based solutions should thus be integrated into urban development to enhance climate resilience and reduce urban energy demands via sustainable spatial planning.

Governance structures and policy frameworks, on the other hand, have emerged as critical determinants in green infrastructure projects. Selim & Saeed (2021) emphasize the importance of multi-stakeholder collaboration, public-private partnerships, and citizen engagement in driving sustainable urban development. South Africa's governance dynamics indeed require inclusive models that will help bridge policy implementation gaps and break persistent energy inefficiencies. Nonetheless, green financing has become a critical enabler for energy-efficient projects, unlocking investment opportunities for infrastructure development. Liu et al. (2021) estimate that $26 trillion in global investments will be needed by 2030 to meet sustainability targets. With the constrained state of South Africa's public finances, mobilizing private capital through innovative mechanisms such as green bonds and targeted investment schemes becomes important. This is in agreement with the work of Taghizadeh-Hesary et al. (2022), who indicate that South Africa can lead in the nascent green bond markets of Africa

Modernization of energy infrastructure is technological in nature. According to Shabalov et al. (2021), the integration of digital technologies will optimize energy systems, decrease consumption, and attract more private investments. In this sense, South Africa's old energy infrastructure might be modernized with the use of such technologies, provided that governance reforms and targeted technical upgrades are pursued. Consequently, it has been established that the influence of energy-intensive industries, such as transportation and industrial production, is well bound with energy efficiency. In addition, Wang & Jiang (2022) establish that transport infrastructure integrated with ecology protection measures promotes green development. This, therefore, forms the view that similar frameworks might be considered by the transport sector in South Africa, decreasing the carbon footprint while sustaining urban expansion.

Institutional quality is a critical determinant of energy efficiency, influencing policy consistency and implementation capacity. Sun et al. (2019) emphasize that robust governance facilitates green innovation and technological diffusion, essential for South Africa's energy transition. Strengthened regulatory mechanisms coupled with targeted investments could accelerate the country's progress toward a greener economy. Another transformative potential lies in the market-driven approaches to green innovation. In this respect, Nassani et al. (2023) investigate how pollution reduction and green technology mediate sustainability. They conclude that policies aimed at innovation-driven market mechanisms might help South Africa's energy sector to improve both energy efficiency and industrial competitiveness.

Global comparative analyses have numerous lessons for the design of South Africa's energy policy. Wang et al. (2023) indicated that fossil fuel efficiency and green infrastructure investments have contributed to long-term green development across Belt and Road economies. It is such dual-track policies that could support an energy transition in South Africa, balancing immediate energy needs with long-term sustainability goals. Moreover, the interaction between energy, transport, and telecommunication infrastructures is considered a cornerstone for sustainable urban development. Xu et al. (2021) note that fragmented infrastructure systems prevent the development of smart and sustainable cities. They further point out that capital investment in integrated human resource development and in strategies for scaling up towns and cities can reduce bottlenecks in urban development. In the South African context, where urbanization pressures persist, ensuring coherence in infrastructure could mitigate system inefficiencies.

Green buildings are essential to this energy-efficient infrastructure. Joseph & Inambao (2021) examined how using the South African Green Building Council rating framework increases energy efficiency and decreases carbon emissions in airports. Their findings, therefore, support embedding environmental standards within national infrastructure policies through the incorporation of broader sustainability objectives. Furthermore, innovative technologies such as those involving landfill gas-to-electricity systems have dual benefits of being socio-economic and environmental. Gumbo & Letlape (2016) illustrate how such technologies will enhance waste management, electrical provision, and stimulate socioeconomic development in disadvantaged communities. Scaling these initiatives in South Africa could alleviate urban sustainability challenges and address the country's energy deficit.

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Green infrastructure enables urban climate resilience through ecosystem services of stormwater management and urban cooling. Bobbns & Culwick (2015) explore the ways in which green infrastructure can counteract the negative effects of climate change in the Gauteng City-Region, despite obstacles such as a lack of localized data and case studies. This indicates a strong need for robust spatial planning and policy integration to support urban sustainability in South Africa. Smart energy systems, driven by innovation in ICT, are critical in mitigating load-shedding and enhancing grid reliability. Mudau & Mhangara (2019) have argued for the modernization of South Africa's energy infrastructure with smart technologies that can stabilize electricity supply. This could ensure industrial development and socio-economic stability amidst recurring power outages.

Historical evolution within South Africa's energy sector demonstrates persistent socio-spatial inequalities. Essex and de Groot (2019) further criticize post-apartheid urban planning models for perpetuating inequalities in electricity access. In this light, they contend that inclusive policies targeting vulnerable populations are critical in ensuring equitable energy transitions—so that no community gets left behind in the country's shift toward renewable energy. Public investment in green infrastructure may have the effect of stimulating economic growth and reducing socio-economic inequalities. Onaran & Oyvat (2024) support expansionary fiscal policies that balance climate action with economic development and suggest increasing investment in green infrastructure and care economies. These policy tools could help South Africa navigate post-pandemic recovery while advancing sustainability objectives.

Governance reforms strike as the very pivotal factors for effective energy policy implementation. Ofori et al. (2022) argued that the qualities of regulation and anti-corruption policies are factors driving success toward energy efficiency in African regions. In this light, improved governance structures might favorably impact South Africa's current energy policy outcomes and, concurrently, contribute to the goal of sustainable economic growth at international levels. Profit-driven motives and high initial costs are some of the institutional constraints that hinder sustainable infrastructure development. According to Jacobs (2021), policy instability and lack of adequate regulatory incentives are major obstacles to private sector investment. Such challenges can be tackled through institutional reforms and new building codes that may mobilize private capital for green infrastructure projects.

Despite the enormous studies on green infrastructure and energy efficiency, there are critical gaps in understanding the integrated impacts on sustainable development in South Africa. Previous studies have often isolated specific aspects such as urban resilience (Bobbns & Culwick, 2015), energy transitions (Essex & de Groot, 2019), and governance reforms (Ofori et al., 2022), without a holistic approach to how these components collectively contribute to resilient and equitable growth. Future research should explore the interplay between governance, regulatory frameworks, and investment incentives while incorporating spatial-temporal analyses of infrastructure scalability and energy transitions.

Methodology

Data and Scope

This paper investigates the relationship between green infrastructure development and energy efficiency in South Africa between 2000 and 2023. The data balance is maintained to reduce imputation, hence the choice of the period. The variables involved in the analysis representing green infrastructural development include renewable energy capacity, renewable energy generation, renewable hydropower capacity, renewable energy investment, greenhouse gas emissions, forest cover, water quality, waste management, and sustainable transportation. The dependent variables include energy intensity, energy consumption capacity, and CO2 emission capacity for energy efficiency. In addition, the study incorporated industrial development and institutional quality as control variables that might moderate the effect of green infrastructures on energy efficiency. Notably, the energy efficiency approach follows the methodology of the BP Energy Institute, which applies a time-dependent equivalence model to energy consumption. Thus, the choice of variables is justified through their empirical and theoretical relevance for the nexus of green infrastructure

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and energy efficiency. In this regard, Table 1 summarizes the variables, measurements, and sources to provide clarity and transparency.

Table 1. Variable, Measurement, Description, and Source

Variable	Measurement	Description	Source
Energy Efficiency Variables:			
Energy intensity	Energy intensity level of primary energy (MJ/$2017 GDP)	EINT	World Bank
Carbon intensity	Carbon intensity of GDP ($kgCO_2e$/2015 USD GDP)	CO2E	World Bank
Primary energy consumption	Primary energy consumption (exajoules)	ECON	BP Energy Institute
Green Infrastructural Development Variables:			
Renewable energy capacity	Renewable energy share of electricity capacity (%)	RCAP	IRENA
Renewable energy generation	Renewable energy share of electricity generation (%)	RGEN	IRENA
Renewable hydropower capacity	Logarithm of Renewable hydropower shares of electricity installed (MW)	HYDR	IRENA
Renewable energy investment	Logarithm of Public investments in multiple renewables (2021 M/USD)	RINV	IRENA
Greenhouse gas emissions	Total greenhouse gas emissions excluding LULUCF (tCO_2e/capita)	GHG	World Bank
Forest cover	Forest area (% of land area)	FRST	World Bank
Water quality	GDP per cubic meter of freshwater withdrawal	WTER	World Bank
Waste management	Methane (CH_4) emissions from waste ($MtCO_2e$)	WSTE	World Bank
Sustainable transportation	Transport services (% of commercial service exports)	TRAN	World Bank
Control/Moderating Variables:			
Industrial development	Industry value added (% of GDP)	INDS	World Bank
Institutional quality	Regulatory Quality: Estimate	INQS	World Governance Index

Source: Author's Compilation, 2024.

Data for these variables are sourced from reputable databases, including the International Renewable Energy Agency, World Bank, BP Energy Institute Statistical Review, and World Governance Index. These sources ensure reliability of data and comparability across the study period. The case study scope of analysis is chosen to be South Africa due to its special position in terms of balance between economic growth and sustainability goals, amidst important challenges of energy transitions and climate change mitigation. The selected time frame from 2000 to 2023 aligns with key policy milestones, including the Renewable Energy Independent Power Producer Procurement Programme and periods of extensive energy reform in South Africa. These years capture sufficient variation in infrastructural investment and energy outcomes, enabling robust longitudinal analyses.

Theoretical Model

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First proposed by Hosier & Dowd (1987), the Energy Ladder Theory provides a robust theoretical framework for understanding the evolution of energy consumption patterns across households, industries, and economies. This theory postulates that as income increases and technological sophistication improves, entities shift from traditional and inefficient energy sources like biomass and coal to modern and efficient energy sources such as electricity and renewables (Hiemstra-Van der Horst & Hovorka, 2008). This "ladder" shows how energy efficiency and environmental sustainability improve as societies develop economically and technologically.

$$E_i(t) = \alpha_0 + \sum_{j=1}^{n} \alpha_j S_j(t) + \beta_1 I_t + \beta_2 Q_t + \varepsilon_t \tag{1}$$

Where $E_i(t)$ is the energy consumption pattern of energy source i at time t, $S_j(t)$ is the share of renewable energy sources j in the energy mix, and I_t is the income or GDP per capita as the proxy for economic advancement, Q_t is the quality of institution influencing energy policy and adoption, and ε_t is the stochastic error term. This equation captures the shift towards renewable energy sources as income and governance structures improve. Energy efficiency improvements—which underpin another component of energy transitions—can be modeled by technological advancements and policy interventions.

$$\pi(t) = \gamma_0 + \gamma_1 T_t + \gamma_2 P_t + v_t \tag{2}$$

Where $\pi(t)$ is the energy efficiency index at time t, T_t represents the adoption of energy-efficient technologies, P_t represents public and private investments in renewable energy infrastructure, and v_t stands for the error term. The equation shows that technological developments and financial input are beneficial to achieve high efficiency that would lower the energy intensity and consumption of energy.

In the South African context, energy ladder theory places great emphasis on the acceleration of transitions along the energy ladder by institutional quality Q_t and public investments P_t. The integration of renewable energy capacity and improved energy efficiency aligns with the theoretical framework emphasizing the role of targeted investments and policies.

Building on the energy ladder theory, this study develops a model that examines the nexus between green infrastructural development and energy efficiency in South Africa. The proposed model captures the dynamic interaction between the variables with consideration for moderating factors such as institutional quality and industrial development. In explaining the relationship between green infrastructural development and energy efficiency, the baseline equation is expressed as:

$$EE_t = \beta_0 + \beta_i GID_{it} + \beta_j V_{jt} + \varepsilon_t \tag{3}$$

To captures the moderating effect of institutional quality and industrial development on the relationship between green infrastructural development and energy efficiency, equation (3) is respecified as:

$$EE_t = \gamma_0 + \gamma_i GID_{it} + \gamma_j V_{jt} + \gamma_i GID_{it} * \gamma_j V_{jt} + \epsilon_t \tag{4}$$

Where;

$$EE_t = f(EINT, ECON, CO2E)_t \tag{5}$$

$$GID_t = f(RCAP, RGEN, HYDR, RINV, GHG, FRST, WTER, WSTE, TRAN)_t \tag{6}$$

$$V_t = f(INSQ, INDS) \tag{7}$$

The descriptions of the variable assignments are notably presented in Table 1 above.

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Estimation Technique

In this study, the Prais-Winsten (1957) model, advanced by Hashimoto (1989) is employed to analyze in detail the relationship that exists between green infrastructural development and energy efficiency in South Africa, while considering the moderating role of institutional quality. The generalized least squares estimator of this model incorporates serial correlation in the time-series data, thus providing an efficient and reliable model. Energy efficiency and green infrastructure are dynamic in nature in South Africa, and the control of autocorrelation is essential in such a series. In light of the Cochrane-Orcutt procedure, the model transforms the regression equation by saving the first observation, therefore minimizing the loss of information. The Prais-Winsten model is specified as:

$$EE_t^* = \beta_0(1-\rho) + \beta_1 GID_t^* + \beta_2 V_t^* + \beta_3(GID_t^* * V_t^*) + \varepsilon_t^* \quad (8)$$

Where:

$$EE_t^* = EE_t - \rho EE_{t-1}, \qquad GID_t^* = GID_t - \rho GID_{t-1}, \qquad V_t^* = V_t - \rho V_{t-1} \quad (9)$$

Here, EE_t^* represents energy efficiency, GID_t^* denotes green infrastructure, and V_t^* captures institutional quality as a moderator. The coefficient ρ represents the first-order autoregressive process AR (1), corrected iteratively until convergence.

Given the time-series nature of the data, the study first checks for stationarity using the Phillips-Perron (1988) and Augmented Dickey-Fuller (1979) unit root tests. Stationarity is a necessary condition to avoid spurious regression results. The ADF test equation is specified as:

$$\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta Y_{t-i} + \varepsilon_t \quad (10)$$

Where:

ΔY_t: First difference of the dependent variable.

α: Constant term.

βt: Trend component.

γY_{t-1}: Lagged level term testing for stationarity.

$\delta_i \Delta Y_{t-i}$: Lagged first differences for correcting autocorrelation.

If $\gamma < 0$ and statistically significant, the series is stationary. The Phillips-Perron test accounts for heteroskedasticity and autocorrelation in the residuals.

If the variables are integrated of the same order, the Johansen (1991) cointegration test examines whether a long-run equilibrium relationship exists among them. The vector error correction model is specified as:

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t \quad (11)$$

Where:

ΔY_t: First-differenced vector of endogenous variables.

Π: Matrix capturing long-run relationships.

Γ_i: Short-run adjustment coefficients.

The number of cointegrating vectors is determined by the rank of Π, using trace and maximum eigenvalue statistics.

After stationarity and possible cointegration were confirmed, the Granger (1969) causality test was used in the study to determine the causal relationship between green infrastructural development and energy efficiency. Granger causality essentially tests whether past values of one variable can predict future values of another. Estimates of the following two equations are obtained:

$$EE_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i EE_{t-i} + \sum_{j=1}^{q} \beta_j GID_{t-j} + \varepsilon_t \tag{12}$$

$$GID_t = \gamma_0 + \sum_{i=1}^{p} \gamma_i GID_{t-i} + \sum_{j=1}^{q} \delta_j EE_{t-j} + \mu_t \tag{13}$$

Where:

p and q: Optimal lags selected using the Akaike Information Criterion (AIC) or Schwarz Bayesian Criterion (SBC).

If the coefficients β_j in the first equation are statistically significant, GID Granger-causes EE. Similarly, if δ_j is significant in the second equation, EE Granger-causes GID. Bidirectional causality occurs if both sets of coefficients are significant.

Empirical Result and Discussion

Result

The descriptive analysis in **Table 2** summarizes the key statistics of variables employed in evaluating the effect of green infrastructural development on energy efficiency in South Africa. In the dependent variables, the means are: energy intensity is 7.65, carbon emission intensity is 1.42, and primary energy consumption is 4.96. Besides, their respective standard deviation is 0.89, 0.16, and 0.35. These therefore reflect a reasonable variability within a trend of relatively stable energy performance. Among the independent variables, renewable energy capacity (6.97) and generation (1.95) demonstrate notable dispersion, with standard deviations of 5.68 and 1.72, reflecting dynamic shifts in South Africa's renewable energy sector. Greenhouse gas emissions (2.17) and forest cover (14.32) are relatively stable, supported by lower standard deviations of 0.30 and 0.20, respectively. Meanwhile, water quality (18.96) and waste management (24.71) reflect higher averages, suggesting significant environmental sustainability efforts. Institutional quality, the moderating variable, has a low mean (0.35) and wide range (-0.22 to 0.82), emphasizing governance challenges. Industrial development (25.26) shows moderate stability (std. dev. = 1.58), indicating steady economic growth. Values of skewness and kurtosis indicate that, indeed, the distributions for most variables are non-normal; for renewable hydropower capacity, skewness equals 2.09, and for renewable energy investment, kurtosis equals 6.35.

Table 2. Descriptive Measures

$Variable$	$Eint$	$Co2e$	$Econ$	$Rcap$	$Rgen$	$Hydr$	$Rinv$	Ghg	$Frst$	$Wter$	$Wste$	$Tran$	$Inds$	$Insq$
Mean	7.65	1.42	4.96	6.97	1.95	2.89	1.03	2.17	14.32	18.96	24.71	17.63	25.26	0.35
Median	7.65	1.40	5.08	3.44	1.07	2.87	0.91	2.24	14.31	18.45	25.00	17.73	24.76	0.42

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Maximum	9.22	1.67	5.35	17.04	5.45	3.13	2.84	2.63	14.66	23.62	28.94	24.74	28.53	0.82
Minimum	6.23	1.12	4.18	2.26	0.48	2.85	-1.40	1.73	14.03	15.09	19.59	12.02	23.35	-0.22
Std. Dev.	0.89	0.16	0.35	5.68	1.72	0.07	1.35	0.30	0.20	2.14	3.16	3.38	1.58	0.32
Skewness	0.15	-0.32	-0.99	0.77	1.06	2.09	-0.25	-0.20	0.15	0.09	-0.20	0.39	0.85	-0.27
Kurtosis	1.80	2.07	2.90	1.86	2.58	6.35	1.90	1.60	1.73	2.45	1.55	2.76	2.67	1.83

Source: Authors' Computations.

Table 3 presents the correlation analysis, showing that renewable energy capacity (-0.82), generation (-0.78), and investment (-0.82) have significant negative impacts on energy intensity. Carbon emission intensity is also negatively related to renewable energy generation (-0.87) and investment (-0.88), hence reflecting emissions reduction through green infrastructure. Greenhouse gas emissions are positively related to carbon emissions of 0.92 and energy intensity of 0.90, showing emissions-driven inefficiency. Forest cover shows positive correlations with energy intensity (0.91) and carbon emissions (0.91), implying deforestation-induced emissions. Institutional quality is strongly negatively associated with greenhouse gas emissions (-0.93) and carbon emissions (-0.95), highlighting governance's sustainability role. Industrial development negatively correlates with emissions but positively with institutional quality (0.69). However, high correlations, such as between renewable energy capacity and generation of 0.97, suggest multicollinearity, while correlations like carbon emissions and renewable energy generation of -0.87 indicate autocorrelation. Their treatment may require the use of various econometric techniques, such as the Prais-Winsten transformation or generalized least squares.

Table 3. Correlation Matrix

$Var.$	$Eint$	$Co2e$	$Econ$	$Rcap$	$Rgen$	$Hydr$	$Rinv$	Ghg	$Frst$	$Wter$	$Wste$	$Tran$	$Inds$	$Insq$
$Eint$	1.00													
$Co2e$	0.91	1.00												
$Econ$	-0.43	-0.42	1.00											
$Rcap$	-0.82	-0.86	0.23	1.00										
$Rgen$	-0.78	-0.87	0.15	0.97	1.00									
$Hydr$	0.36	0.32	-0.73	-0.14	-0.16	1.00								
$Rinv$	-0.82	-0.88	0.30	0.78	0.77	-0.16	1.00							
Ghg	-0.90	-0.92	0.69	0.78	0.73	-0.51	0.80	1.00						
$Frst$	0.91	0.91	-0.68	-0.82	-0.77	0.51	-0.79	-0.97	1.00					
$Wter$	0.36	0.47	0.35	-0.74	-0.77	-0.30	-0.44	-0.24	0.28	1.00				
$Wste$	-0.93	-0.92	0.66	0.80	0.74	-0.50	0.80	0.98	-0.99	-0.24	1.00			
$Tran$	0.78	0.73	-0.55	-0.78	-0.72	0.45	-0.58	-0.81	0.84	0.39	-0.82	1.00		
$Inds$	0.77	0.70	-0.78	-0.57	-0.48	0.64	-0.63	-0.85	0.88	-0.01	-0.86	0.79	1.00	
$Insq$	0.87	0.95	-0.44	-0.91	-0.89	0.34	-0.83	-0.93	0.91	0.52	-0.91	0.74	0.69	1.00

Source: Authors' Computations.

Stationarity tests shown in **Table 4** indicate that all variables, except renewable hydropower capacity, are non-stationary at levels, since the Phillips-Perron and Augmented Dickey-Fuller test statistics failed to reject the null hypothesis of a unit root. However, after first differencing, all the variables are stationary at either 1% or 5% significance level. Renewable hydropower capacity is stationary at levels based on the Dickey-Fuller test, indicating that it is integrated of order zero, while all other green infrastructural development variables are integrated of order one. The industrial development and the moderating variable of institutional quality also turn out to be stationary after differencing. These results confirm the Johansen cointegration technique as necessary in order to address the long-run equilibrium relationship in the model.

Table 4. Stationarity Tests

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Variable	Phillips – Perron Test			Dickey – Fuller Test		
	Level	1st Diff.	Order	Level	1st Diff.	Order
Eint	-1.116 (0.692)	-10.230*** (0.000)	I (1)	-1.308 (0.608)	-4.991*** (0.001)	I (1)
Co2e	0.421 (0.979)	-4.415*** (0.002)	I (1)	0.325 (0.975)	-4.284*** (0.004)	I (1)
Econ	-2.242 (0.198)	-5.513*** (0.000)	I (1)	-2.215 (0.207)	-5.508*** (0.000)	I (1)
Rcap	0.554 (0.985)	-2.528* (0.093)	I (1)	0.077 (0.956)	-2.634* (0.092)	I (1)
Rgen	1.282 (0.998)	-2.504* (0.098)	I (1)	1.684 (0.999)	-2.548* (0.099)	I (1)
Hydr	-2.561 (0.115)	-6.964*** (0.000)	I (1)	-3.925** (0.008)	-6.449*** (0.000)	I (0)
Rinv	-1.474 (0.529)	-10.765*** (0.000)	I (1)	-1.652 (0.441)	-4.789*** (0.001)	I (1)
Ghg	-0.162 (0.931)	-4.369** (0.003)	I (1)	-0.241 (0.920)	-4.325** (0.003)	I (1)
Frst	-1.707 (0.415)	-5.420*** (0.000)	I (1)	Nil	Nil	Nil
Wter	-0.699 (0.828)	-3.616** (0.014)	I (1)	-0.494 (0.875)	-3.641** (0.013)	I (1)
Wste	-1.036 (0.722)	-3.907** (0.007)	I (1)	-1.036 (0.722)	-3.907** (0.007)	I (1)
Tran	-1.436 (0.547)	-4.217** (0.004)	I (1)	-1.461 (0.535)	-4.225** (0.004)	I (1)
Inds	-2.183 (0.217)	-4.628** (0.002)	I (1)	-1.957 (0.302)	-4.622** (0.002)	I (1)
Insq	0.736 (0.990)	-5.513*** (0.000)	I (1)	0.750 (0.991)	-5.492*** (0.000)	I (1)

Source: Authors' Computations.

The cointegration tests in **Table 5** confirm the existence of a long-run equilibrium relationship between energy efficiency and green infrastructural development in South Africa. Indeed, two cointegrating equations were revealed by the trace test at the 5% significance level, with the test statistics of 99.39 and 25.34 respectively, exceeding the critical values of 29.80 and 15.49 respectively. In the same vein, the maximum eigenvalue test confirms two cointegrating relationships with test statistics of 74.05 and 23.84, respectively, against corresponding critical values of 21.13 and 14.26. These results imply that green infrastructural development move together with energy efficiency indicators over the long run.

Table 5. Cointegration Tests

Unrestricted Cointegration Rank Test (Trace)				
Hypothesized		Trace	0.05	
No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
None *	0.965465	99.38696	29.79707	0.0000
At most 1 *	0.661594	25.33987	15.49471	0.0012
At most 2	0.066022	1.502654	3.841466	0.2203
Trace test indicates 2 cointegrating eqn(s) at the 0.05 level, * denotes rejection of the hypothesis at the 0.05 level, and **MacKinnon-Haug-Michelis (1999) p-values				
Unrestricted Cointegration Rank Test (Maximum Eigenvalue)				
Hypothesized		Max-Eigen	0.05	

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No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
None *	0.965465	74.04709	21.13162	0.0000
At most 1 *	0.661594	23.83722	14.26460	0.0012
At most 2	0.066022	1.502654	3.841466	0.2203
Max-eigenvalue test indicates 2 cointegrating eqn(s) at the 0.05 level, * denotes rejection of the hypothesis at the 0.05 level, and **MacKinnon-Haug-Michelis (1999) p-values				

Source: Authors' Computations.

Table 6 presents the relationship between green infrastructural development and energy efficiency indicators in South Africa. The renewable energy capacity, therefore, does not indicate any significant effect on energy intensity and primary energy consumption. However, it has a positive and significant impact on the carbon emission intensity (0.036) at a 1% significance level. Therefore, the generation of renewable energies significantly reduces both carbon emission intensity (-0.103, $p<0.01$) and primary energy consumption (-0.214, $p<0.01$), with a marginal effect on energy intensity (-0.357, $p<0.10$). Hydropower capacity negatively affects carbon emission intensity (-0.405, $p<0.01$), which means that the higher one develops hydropower, the more efficient the emission reduction will be. However, it is insignificant in energy intensity and primary energy consumption. The results also show that forest cover has a negative effect on energy intensity (-5.721, $p<0.05$) and primary energy consumption (-4.738, $p<0.01$), indicating that a reduction in deforestation significantly contributes to energy efficiency improvements. Waste management has a negative and significant effect on energy intensity (-0.492, $p<0.01$), carbon emission intensity (-0.044, $p<0.01$), and primary energy consumption (-0.231, $p<0.01$). However, institutional quality does not show a significant relationship with regard to energy intensity, carbon emission intensity, or primary energy consumption, which provides evidence for the fact that governance quality does not solely ensure strong direct influence in this context. In contrast, greenhouse gas emissions and transport management are significantly negative to affect carbon intensity, having respective coefficients of -0.418 and -0.010 at 5% and 10% significant levels. However, industrial development has a positive and negligible impact on carbon intensity, with a coefficient of 0.017 at 10% significant level.

Table 6: Effect of Green Infrastructural Development on Energy Efficiency in South Africa

$Variable$	$Eint$	$Co2e$	$Econ$
$Rcap$	0.014 (0.852)	0.036*** (0.000)	0.007 (0.816)
$Rgen$	-0.357* (0.065)	-0.103*** (0.000)	-0.214** (0.009)
$Hydr$	-1.422 (0.487)	-0.405*** (0.000)	-1.114 (0.158)
$Rinv$	-0.007 (0.960)	0.000 (0.986)	0.008 (0.894)
Ghg	-2.157 (0.425)	-0.418** (0.012)	0.577 (0.632)
$Frst$	-5.721** (0.014)	-0.163 (0.258)	-4.738** (0.000)
$Wter$	0.113 (0.401)	0.033** (0.006)	0.042 (0.415)
$Wste$	-0.492** (0.003)	-0.044** (0.000)	-0.231** (0.000)
$Tran$	-0.084 (0.462)	-0.010* (0.095)	-0.038 (0.399)
$Inds$	0.268 (0.160)	0.017* (0.064)	0.098 (0.222)

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$Insq$	-2.783 (0.307)	-0.177 (0.176)	-0.372 (0.717)
C	104.681** (0.007)	6.055** (0.017)	78.369** (0.000)
R^2	0.963	0.999	0.993
F	89.415	1641.215	74.169
$Rmse$	0.333	0.018	0.119
N	24	24	24

Source: Authors' Computations.

Results in **Table 7** examine the moderating role of institutional quality in the relationship between green infrastructural development and energy efficiency in South Africa. Renewable energy capacity significantly increases energy intensity (0.599, $p<0.01$) and primary energy consumption (0.210, $p<0.05$) but has a marginal positive effect on carbon emission intensity (0.045, $p<0.10$). However, the interaction term of renewable energy capacity and institutional quality presents a mitigating effect on energy intensity at -0.337 ($p<0.10$), suggesting that good governance can alleviate the inefficiencies in renewable energy capacity. Renewable energy generation reduces energy intensity significantly at -3.350 ($p<0.01$) and primary energy consumption at -0.955 ($p<0.05$), while its interaction with institutional quality further enhances energy efficiency through a significant reduction in energy intensity at -3.490 ($p<0.01$). Hydropower capacity increases energy intensity positively (98.194, $p<0.01$), but this effect is partially offset by its interaction with institutional quality (-132.680, $p<0.01$), which may underpin that strong institutions are effective in making hydropower development inefficiencies curtailed. Renewable energy investment decreases energy intensity negatively (-1.999, $p<0.01$), and the interaction between institutional quality positively mediates the effect (4.355, $p<0.01$), meaning that good governance acts as the linchpin to optimize such investment outcomes. Greenhouse gas emissions positively influence energy intensity (5.577, $p<0.01$), but no significant moderation by institutional quality is observed. Forest cover significantly reduces energy intensity (-33.286, $p<0.01$), with its interaction with institutional quality also yielding a positive moderating effect (29.556, $p<0.01$). Water quality and waste management show significant negative impacts on energy intensity (-0.651, $p<0.01$; -1.145, $p<0.01$, respectively), with water quality benefiting from institutional moderation (1.296, $p<0.01$). Sustainable transportation positively influences energy intensity (0.435, $p<0.01$), but interaction with institutional quality decreases inefficiencies (-0.812, $p<0.01$). Conclusively, the findings highlight the fact that institutional quality serves as an important moderator for influencing positive impacts of green infrastructural development on energy efficiency and lessening adverse impacts.

Table 7. Moderating Role of Institutional Quality in Influencing the Impact of Green Infrastructural Development on Energy Efficiency in South Africa

$Variable$	$Eint$	$Co2e$	$Econ$
$Rcap$	0.599** (0.001)	0.045* (0.098)	0.210** (0.041)
$Insq$	-33.874 (0.701)	-74.550 (0.233)	123.282 (0.525)
$Rcap * Insq$	-0.337* (0.084)	-0.055 (0.332)	-0.204 (0.269)
$Rgen$	-3.350** (0.001)	-0.176 (0.166)	-0.955** (0.054)
$Rgen * Insq$	-3.490** (0.009)	0.362 (0.345)	-0.029 (0.981)
$Hydr$	98.194** (0.002)	-3.723 (0.445)	13.466 (0.408)

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$Hydr * Insq$	-132.680** (0.002)	4.635 (0.474)	-17.268 (0.426)
$Rinv$	-1.999** (0.002)	0.047 (0.597)	-0.200 (0.520)
$Rinv * Insq$	4.355** (0.003)	-0.154 (0.497)	0.536 (0.499)
Ghg	5.577** (0.008)	-0.166 (0.797)	-4.333* (0.101)
$Ghg * Insq$	0.122 (0.979)	2.403 (0.449)	13.743 (0.218)
$Frst$	-33.286** 0.001	0.211 0.854	-4.317 0.292
$Frst * Insq$	29.556** (0.004)	4.004 (0.198)	-4.732 (0.612)
$Wter$	-0.651 (0.001)	-0.003 (0.895)	0.024 (0.754)
$Wter * Insq$	1.296** (0.003)	0.086 (0.345)	0.189 (0.542)
$Wste$	-1.145** (0.004)	0.012 (0.912)	0.254 (0.491)
$Wste * Insq$	-0.711 (0.119)	-0.106 (0.711)	-1.701 (0.130)
$Tran$	0.435** (0.001)	0.015 (0.569)	-0.168 (0.115)
$Tran * Insq$	-0.812*** (0.000)	-0.028 (0.472)	0.174 (0.224)
C	225.857** (0.001)	8.857 (0.260)	34.092 (0.202)
R^2	1.000	1.000	1.000
F	-1.407	-0.998	-0.972
Rho	0.054	0.021	0.071
$Rmse$	23	24	24

Source: Authors' Computations.

In **Table 8**, the Granger causality analysis presents various causal dynamics between the green infrastructural development indicators and energy efficiency measures in South Africa. Energy intensity and renewable energy generation are characterized by a bidirectional causality; hence, both variables are statistically influential on each other, reinforcing the notion of mutual reinforcement. Similarly, a feedback relationship is observed between energy intensity and renewable energy investment, with energy intensity Granger causing renewable energy investment, while carbon emission intensity and primary energy consumption also Granger cause renewable energy investment. However, renewable energy investment does not Granger cause any energy efficiency measure, indicating an asymmetric causal link.

Unidirectional causality is observed where forest cover significantly Granger causes energy intensity and carbon emission intensity, highlighting its critical role in environmental sustainability. Similarly, greenhouse gas emissions Granger cause energy intensity, indicating that rising emissions prompt energy efficiency interventions. Waste management reveals a bidirectional causality with carbon emission intensity, reflecting a mutual environmental impact. Additionally, institutional quality Granger causes energy intensity, while energy intensity also Granger causes institutional quality, revealing strong feedback that underlines the role

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of governance in energy policy. No other causal relationships were found to exist with any of the energy efficiency indicators for water quality or industrial development.

Table 8. Causality Test

Hypotheses	*F-stat. Prob.*	*Hypotheses*	*F-stat. Prob.*	*Hypotheses*	*F-stat. Prob.*
$Rcap \rightarrow Eint$	1.048 (0.372)	$Rcap \rightarrow Co2e$	0.445 (0.648)	$Rcap \rightarrow Econ$	2.027 (0.162)
$Eint \rightarrow Rcap$	4.394** (0.029)	$Co2e \rightarrow Rcap$	3.343* (0.060)	$Econ \rightarrow Rcap$	1.362 (0.283)
$Rgen \rightarrow Eint$	3.801** (0.043)	$Rgen \rightarrow Co2e$	2.651 (0.100)	$Rgen \rightarrow Econ$	1.453 (0.262)
$Eint \rightarrow Rgen$	4.311** (0.031)	$Co2e \rightarrow Rgen$	2.418 (0.119)	$Econ \rightarrow Rgen$	3.356** (0.059)
$Hydro \rightarrow Eint$	1.686 (0.215)	$Hydro \rightarrow Co2e$	2.957* (0.079)	$Hydro \rightarrow Econ$	2.157 (0.146)
$Eint \rightarrow Hydro$	4.107** (0.035)	$Co2e \rightarrow Hydro$	0.331 (0.723)	$Econ \rightarrow Hydro$	3.062* (0.073)
$Rinv \rightarrow Eint$	0.979 (0.396)	$Rinv \rightarrow Co2e$	1.061 (0.368)	$Rinv \rightarrow Econ$	0.444 (0.649)
$Eint \rightarrow Rinv$	14.793*** (0.000)	$Co2e \rightarrow Rinv$	9.335** (0.002)	$Econ \rightarrow Rinv$	6.532** (0.008)
$Ghg \rightarrow Eint$	5.045** (0.019)	$Ghg \rightarrow Co2e$	2.398 (0.121)	$Ghg \rightarrow Econ$	0.217 (0.807)
$Eint \rightarrow Ghg$	0.170 (0.845)	$Co2e \rightarrow Ghg$	2.536 (0.109)	$Econ \rightarrow Ghg$	0.878 (0.434)
$Frst \rightarrow Eint$	6.694** (0.007)	$Frst \rightarrow Co2e$	5.831** (0.012)	$Frst \rightarrow Econ$	0.354 (0.707)
$Eint \rightarrow Frst$	0.211 (0.812)	$Co2e \rightarrow Frst$	0.713 (0.504)	$Econ \rightarrow Frst$	2.449 (0.116)
$Wter \rightarrow Eint$	1.461 (0.260)	$Wter \rightarrow Co2e$	1.221 (0.320)	$Wter \rightarrow Econ$	1.242 (0.314)
$Eint \rightarrow Wter$	3.800** (0.043)	$Co2e \rightarrow Wter$	2.447 (0.116)	$Econ \rightarrow Wter$	0.509 (0.610)
$Wste \rightarrow Eint$	6.759** (0.007)	$Wste \rightarrow Co2e$	2.835* (0.087)	$Wste \rightarrow Econ$	0.122 (0.886)
$Eint \rightarrow Wste$	0.491 (0.621)	$Co2e \rightarrow Wste$	5.079** (0.019)	$Econ \rightarrow Wste$	3.510** (0.053)
$Tran \rightarrow Eint$	0.956 (0.404)	$Tran \rightarrow Co2e$	2.961* (0.079)	$Tran \rightarrow Econ$	1.161 (0.337)
$Eint \rightarrow Tran$	4.004** (0.038)	$Co2e \rightarrow Tran$	3.627** (0.049)	$Econ \rightarrow Tran$	1.666 (0.218)
$Inds \rightarrow Eint$	1.140 (0.343)	$Inds \rightarrow Co2e$	2.082 (0.155)	$Inds \rightarrow Econ$	0.656 (0.531)
$Eint \rightarrow Inds$	0.350 (0.709)	$Co2e \rightarrow Inds$	0.419 (0.664)	$Econ \rightarrow Inds$	1.713 (0.210)
$Insq \rightarrow Eint$	12.509** (0.001)	$Insq \rightarrow Co2e$	3.318* (0.061)	$Insq \rightarrow Econ$	1.066 (0.367)
$Eint \rightarrow Insq$	4.085** (0.036)	$Co2e \rightarrow Insq$	2.057 (0.159)	$Co2e \rightarrow Insq$	3.889** (0.041)

Source: Authors' Computations.

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Discussion

The findings of this study provide a vital understanding of the interplay between green infrastructural development and energy efficiency within the South African context, a country grappling with significant energy and environmental challenges. Evidence that renewable energy generation significantly reduces carbon emission intensity and primary energy consumption suggests a positive trajectory toward sustainable energy systems. This also aligns with Khoshnava et al. (2020), who stressed the contribution of green infrastructure to linking energy systems with greater sustainability goals. However, the fact that investment in renewable energy does not significantly influence energy intensity shows systemic inefficiencies such as delayed project completions and inadequate technological adoptions, issues also underlined by Taghizadeh-Hesary et al. (2022).

The role of institutional quality as a moderator has become instrumental in addressing the question of inefficiency in green infrastructure. Strong governance amplifies the effectiveness of renewable energy projects and hydropower capacity to realize these investments as actual energy efficiency gains. Sun et al. (2019) stress that institutional quality provides an enabling environment for energy transitions through a reduction in policy uncertainty and promotion of transparency. In South Africa, where governance challenges often hinder development initiatives, such findings underline the necessity for institutional reforms to maximize the potential of green infrastructure.

The negative relationship between forest cover and energy efficiency indicators further underlines the environmental sustainability dimension. Reduced deforestation significantly enhances energy efficiency, therefore reestablishing that environmental conservation and energy policies go hand in glove, as were observed by Latasa et al. (2021). In like manner, effective strategies of waste management emerge as critical tools to help enhance energy efficiency with regard to addressing urban environmental challenges, echoing Nassani et al. (2023). However, the contribution of industrial development is negligible to energy efficiency, which signals that South Africa's industrial sector may not be aligned with the green growth objective. This therefore confirms Essex and de Groot's (2019) argument that structural inefficiencies and outdated models of industries serve as a barrier to energy transitions. There is a need for stronger integration of green infrastructure strategies into industrial policies in order to overcome these challenges.

The causality analysis finally reveals complex feedback mechanisms between governance, energy efficiency, and green infrastructural investments. This implies that energy policy needs to be pursued in a synergistic manner, as emphasized by Liu et al. (2021), because there is bidirectional causality between energy intensity and renewable energy generation. Therefore, the twin problems of energy inefficiency and environmental degradation facing South Africa's energy sector call for coordination in investments, governance, and technological innovation.

Conclusion and Policy Recommendations

Using the Energy Ladder Theory, this paper examines green infrastructural development and energy efficiency in South Africa within the period from 2000 to 2023. Applying the Prais-Winsten estimation technique and the Granger causality test, the paper had strong evidence on the role of institutional quality as a moderator. Major findings show that renewable energy capacity and generation, forest cover preservation, waste management, and hydropower development have an immense impact on energy efficiency by reducing carbon emissions and consumption of energy. However, though impactful, renewable energy investment requires better governance to optimize the outcomes. Supportive evidence from the Granger causality test confirmed the presence of bidirectional and feedback relationships, underscoring the dynamic interaction between institutional quality, energy policies, and sustainability objectives. These findings confirm that the quality of institutions is not merely a supplementary factor but

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a critical enabler of realizing the potential of green infrastructure investments in enhancing energy efficiency.

In this regard, policymakers should strengthen institutional frameworks by making regulations more transparent, introducing performance-based incentives, and holding individuals accountable. Any expansion of renewable energy investments should be done alongside governance reforms that ensure efficiency and environmental compliance. Investments in afforestation, water management, and sustainable transport need to be promoted hand in hand with policies that reduce greenhouse gas emissions. Public-private partnerships can be encouraged to enhance financing, and real-time data-driven monitoring frameworks can track energy efficiency. South Africa's sustainable energy future indeed needs integrated policy approaches.

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Appendix: