

Bridging Africa's Power Gap: The Role of Renewable Energy in an Era of Electricity Reforms

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Abstract

This study examined how renewable electricity penetration improves power sector reliability in Sub-Saharan Africa and evaluates the moderating role of electricity sector reforms in shaping this relationship. Despite substantial investments in renewable energy across the region, power systems remain fragile, raising concerns about whether renewable expansion alone can enhance reliability without complementary institutional reforms. Using panel data for 49 Sub-Saharan African countries over the period 2000–2022, the study employed logistic regression to estimate the probability of power sector fragility and OLS models for robustness, complemented by interaction and threshold analysis to capture non-linear effects. The results showed that higher GDP per capita significantly reduces the likelihood of power fragility. Renewable electricity penetration, when considered independently, does not significantly improve reliability; however, its interaction with regulatory reforms reveals a statistically significant reduction in fragility in reform-oriented systems. Furthermore, the relationship between renewable penetration and fragility is non-linear: countries with renewable shares between 30–50 percent exhibit the lowest probability of fragility, whereas extremely high renewable shares are associated with increased instability, likely reflecting integration and grid management constraints. The findings suggest that renewable expansion alone is insufficient to ensure reliability; institutional reforms that strengthen regulatory quality and investment efficiency are critical. Policymakers should therefore prioritize coordinated reform strategies alongside renewable deployment to enhance power system stability in the region.

Keywords: Renewable Energy Penetration, Electricity Reforms, Power Fragility, Power Gap, Energy Transition, Sub-Saharan Africa.

Introduction

The global energy system is undergoing a structural transition toward low-carbon electricity generation. Renewable energy deployment has accelerated significantly over the past decade, driven by technological innovation, policy commitments, and rapidly declining costs (IRENA, 2023). While advanced economies have integrated renewable technologies into relatively stable electricity systems, the benefits of this transition remain uneven across regions. Sub-Saharan Africa continues to face persistent electricity shortages, frequent outages, and chronic system fragility. Approximately 600 million people in Africa lack access to electricity, and unreliable supply remains a binding constraint on economic

productivity, industrialization, and human development (IEA, 2023). In this context, energy poverty reflects not only an access deficit but also a crisis of reliability.

A substantial body of peer-reviewed literature identifies renewable energy as a driver of energy security, economic growth, and environmental sustainability (Apergis & Payne, 2010; Omri et al., 2015; Bhattacharya et al., 2016). Evidence from developing economies suggests that renewable energy expansion can reduce import dependence and support long-run growth dynamics (Apergis & Payne, 2014). In African contexts, decentralized renewable systems have been shown to improve rural electrification outcomes and expand energy equity (Trotter, 2016; Moner-Girona et al., 2016). However, the empirical evidence remains inconclusive regarding whether renewable penetration directly enhances power system reliability, particularly in countries characterized by weak transmission networks and limited institutional capacity (Bazilian et al., 2012; Nussbaumer et al., 2012; Pueyo, 2018). In fragile electricity markets, rapid renewable integration may introduce intermittency and coordination challenges that strain already constrained grid systems.

Parallel to renewable expansion, many Sub-Saharan African countries have implemented electricity sector reforms aimed at improving efficiency, attracting private investment, and strengthening regulatory performance. Reform initiatives commonly include unbundling vertically integrated utilities, liberalizing generation markets, establishing independent regulatory authorities, and restructuring tariff systems (Eberhard et al., 2017; Jamasb et al., 2015). Although existing research documents mixed outcomes regarding the impact of reforms on efficiency and access (Sen & Jamasb, 2012; Zhang et al., 2008), relatively few studies examine whether institutional reforms condition the effectiveness of renewable energy deployment in enhancing power reliability. Since institutional quality and regulatory strength are central determinants of infrastructure performance in developing economies (Calderón & Servén, 2010), renewable energy outcomes are likely to depend significantly on the reform environment within which they are implemented.

Despite increasing renewable capacity and widespread reform efforts, power systems across Sub-Saharan Africa remain fragile. Climate-related shocks further compound system vulnerability, as demonstrated by drought-induced hydropower disruptions in countries such as Zambia and Ghana (World Bank, 2023). At the same time, Africa possesses renewable energy potential far exceeding current utilization levels (IRENA, 2023), yet investment flows remain disproportionately low (IEA, 2023). This paradox raises an important empirical question: does renewable energy penetration strengthen electricity system reliability, and does the answer depend on the depth of electricity sector reforms?

The existing literature largely analyzes renewable energy expansion and electricity sector reforms in isolation. Consequently, limited empirical evidence is available on whether renewable penetration improves power reliability under varying institutional reform contexts. The absence of systematic cross-country analysis integrating renewable deployment and reform intensity represents a significant empirical and policy gap.

Problem Statement

Access to stable electricity supply remains a critical challenge in many African countries where erratic supply and persistent power shortages limit human wellbeing and hinder economic productivity (Adamu, Yelwa & Hassan, 2020; Akindele-Sotunbo et al., 2022; Nneze, Ezeodili & Nze 2024). Climate change further complicates fossil fuel reliance, as seen in drought-induced hydropower failures in Zambia and Ghana (World Bank, 2023). The continent's energy security, therefore, demands a shift to more resilient, decentralized solutions. While several reforms have been carried out in the electricity sector, such as unbundling, regulatory restructuring and public-private partnership with the aim of improving performance in the sector, many countries continue to experience a widening energy access gap in Africa (Eberhard et al., 2017; CLG Global, 2025; Bjerde, 2025).

Africa's renewable energy potential is 100 times greater than its current consumption (IRENA, 2023), yet only 2% of global RE investments flow here (IEA, 2023). Early failures, such as underfunded solar projects in the 2000s, created skepticism, but technological advancements and cost reductions have revived optimism. Solar PV costs, for instance, have dropped by 82% since 2010, making it the cheapest new-build power source in most African countries (IRENA, 2023). This economic viability, paired with energy access needs, positions renewables as the continent's most pragmatic solution. Therefore, expanding access to renewable energy provides a critical pathway to address this gap. Beyond environmental benefits, decentralized and off-grid renewable systems can contribute to energy equity by reaching underserved communities, particularly in rural and peri-urban areas (Trotter, 2016).

Although renewable energy capacity has expanded and electricity sector reforms is becoming increasingly widespread across Sub-Saharan Africa, power systems in the region remain fragile and unreliable. The existing literature largely examined renewable energy expansion and electricity reforms in isolation, offering limited empirical insight into whether renewable energy penetration enhances power system reliability under varying institutional reform contexts. Consequently, the absence of robust evidence on the interaction between renewable deployment and electricity sector reforms constitutes a significant empirical and policy gap. This study addresses this gap by pursuing the following objectives:

1. To examine the relationship between renewable energy penetration and power sector reliability in Sub-Saharan Africa.
2. determine whether a threshold level of renewable energy penetration exists beyond which power reliability improves or deteriorates.
3. evaluate whether electricity sector reforms moderate the relationship between renewable energy penetration and power sector reliability.

By employing cross-country panel analysis with interaction and threshold modeling techniques, this study contributes to the literature on energy transitions, infrastructure

reliability, and institutional reform in developing economies, providing policy-relevant insights for coordinated renewable and regulatory strategies.

Literature Review

The empirical literature on renewable energy has primarily focused on its macroeconomic implications. Panel-based studies consistently find that renewable energy consumption contributes positively to long-run economic growth, although the direction and magnitude of causality vary across country groups (Apergis & Payne, 2010; Apergis & Payne, 2014; Omri et al., 2015; Bhattacharya et al., 2016). These findings position renewable energy as a productive input capable of enhancing energy security and reducing fossil fuel dependence in developing economies. However, while the renewable-growth nexus is well established, considerably less attention has been devoted to sector-level outcomes such as electricity reliability, grid stability, or power system fragility.

In African contexts, renewable energy has been promoted not only as a growth-enhancing resource but also as a mechanism for improving energy access and equity. Decentralized renewable systems, particularly solar-based mini-grids and off-grid technologies, have demonstrated positive impacts on rural electrification and service expansion (Trotter, 2016; Moner-Girona et al., 2016). These studies emphasize the distributive benefits of renewable deployment in underserved regions. Nevertheless, improvements in access do not necessarily translate into improvements in system reliability. Grid-connected renewable expansion introduces technical and operational challenges, particularly in countries characterized by aging transmission infrastructure and limited system balancing capacity. Concerns regarding renewable integration in fragile electricity systems have been highlighted in broader energy transition debates. Bazilian et al. (2012) argue that energy system transformation in developing economies must account for infrastructure readiness and institutional capacity constraints. Similarly, Nussbaumer et al. (2012) emphasize that energy access metrics often overlook service quality dimensions, including reliability and continuity. Pueyo (2018) further notes that institutional and financial weaknesses may undermine renewable project sustainability in African markets. Collectively, this literature suggests that renewable energy outcomes are contingent on system-level and institutional conditions, yet empirical verification of these conditional effects remains limited.

Parallel to renewable expansion, electricity sector reforms have reshaped governance structures across Sub-Saharan Africa since the 1990s. Reform programs typically involve vertical unbundling, private sector participation, tariff restructuring, and the establishment of independent regulatory authorities (Eberhard et al., 2017; Jamasb et al., 2015). Theoretical arguments underlying these reforms posit that competition, regulatory independence, and market-based pricing enhance efficiency and investment incentives. However, empirical evidence on reform outcomes is mixed. Cross-country analyses indicate that performance improvements depend heavily on regulatory credibility and institutional depth (Zhang et al., 2008; Sen & Jamasb, 2012).

Institutional quality more broadly has been identified as a fundamental determinant of infrastructure productivity in developing economies. Calderón and Servén (2010) demonstrate that governance indicators significantly influence the growth impact of infrastructure investment. In the electricity sector, weak regulatory enforcement, political interference, and financial instability of utilities can offset the expected benefits of reform initiatives. Consequently, reform measures may not directly guarantee improved reliability; rather, their effectiveness depends on implementation quality and broader institutional context.

Despite these insights, the renewable energy and electricity reform literatures have largely evolved in parallel. Studies on renewable energy tend to emphasize growth, access, and environmental outcomes, while reform studies focus on efficiency, competition, and privatization effects. Limited empirical work integrates these strands to examine whether electricity sector reforms condition the relationship between renewable energy penetration and power system reliability. This omission is particularly significant in Sub-Saharan Africa, where both renewable deployment and reform efforts have expanded but power fragility persists.

Conceptually, electricity sector reforms may moderate the renewable–reliability nexus through several mechanisms. First, credible regulatory institutions can reduce investment risk, facilitating complementary investments in transmission and grid management necessary for renewable integration. Second, tariff reforms and improved utility governance can strengthen financial sustainability, enabling maintenance and system upgrades that enhance reliability. Third, regulatory independence may improve coordination between public and private actors, reducing integration bottlenecks. Conversely, in weak reform environments, renewable expansion without adequate grid reinforcement or regulatory oversight may exacerbate volatility and increase outage risk. The existing literature therefore points to a conditional rather than automatic relationship between renewable energy penetration and electricity reliability. Yet empirical analysis explicitly testing this moderating role of electricity sector reforms across African countries remains scarce. By integrating renewable penetration measures with reform intensity indicators within a unified empirical framework, this study advances understanding of how institutional structures shape infrastructure performance in developing electricity markets.

Theoretical Framework

This study adopted an extended production function framework to model power sector reliability as the outcome of energy inputs, productive capacity, and institutional quality. Drawing from the Cobb–Douglas (Douglas & Cobb, 1928) and CES (Arrow et al., 1961) traditions, the electricity system is conceptualized as a productive structure in which multiple inputs jointly determine system performance.

Let power sector reliability be denoted by R_i representing the capacity of country i 's electricity system to deliver stable and continuous supply. We specify an extended Cobb–Douglas production function of the form:

$$R_i = A_i \cdot RE_i^\alpha \cdot FFE_i^\beta \cdot K_i^\gamma \cdot L_i^\delta \cdot I_i^\theta \dots\dots\dots 1$$

Where:

R = Power sector reliability

A = Total factor productivity

RE_i = Renewable energy inputs

FFE_i = Traditional energy inputs

K = Physical capital

L = Human capital

I = Institutional quality

While $\alpha, \beta, \gamma, \delta, \theta$ are output elasticities.

Within this framework, the reliability of power supply is treated as a productive outcome emerging from the efficient combination of these factors, that is a multiplicative structure that assumes constant output elasticities and positive marginal contributions of each input. Renewable energy penetration contributes by diversifying supply sources and enhancing system resilience (captured by α), while sector reforms and institutional quality improve the conversion efficiency of inputs into reliable output (captured by θ).

Taking natural logarithms yields the linearized form which motivates the empirical estimation strategy:

$$\ln R_i = \ln A_i + \alpha \ln RE_i + \beta \ln FFE_i + \gamma \ln K_i + \delta \ln L_i + \theta \ln I_i + \varepsilon_i \dots\dots\dots 2$$

The choice of the production function as the theoretical framework for this study is thus premised on the fact that the theory focuses on quantifiable input–output relationships, making it particularly suited for empirical estimation and policy interpretation. Furthermore, the extended Cobb–Douglas/CES framework provides an analytically tractable foundation for the estimation of moderating and interaction effects within a logistic regression framework.

In practice however, power system performance in many Sub-Saharan African countries exhibits threshold behavior; systems are either functionally reliable or fragile. Let R_i^* denote latent reliability derived from the production function above. Observed power fragility is defined as:

$$Fragility_i = \begin{cases} 1 & \text{if } R_i^* < R^{threshold} \\ 0 & \text{otherwise} \end{cases}$$

Thus, fragility is observed when latent reliability falls below a critical threshold. Substituting the log–linear form into a probability framework:

$$P(fragility_i = 1) = F(\beta_0 + \beta_1 RE_i + \beta_2 GDPPC_i + U_i) \dots\dots\dots 3$$

Where $F(.)$ is the logistic cumulative distribution function.

The logistic regression model is therefore theoretically grounded in the production function framework, as it estimates the probability that productive reliability falls below a minimum operational level.

Model Specification

To estimate the first objective which is to examine the relationship between renewable energy access and power reliability in Africa; the following logistic regression model is specified.

$$\text{logit}(\text{fragility} = 1) = \beta_0 + \beta_1(RE_i) + \beta_2(GDPPC) + \varepsilon_i$$

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Formally, the logistic regression model is specified as:

$$P(\text{fragility}_i = 1) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 RE_i + \beta_2 GDPPC_i + \varepsilon_i)}} \dots\dots\dots 5$$

The production function framework also allows for non-linear effects of renewable penetration. If renewable integration generates reliability gains only after complementary infrastructure capacity is achieved, then α may vary across penetration levels. To test this in objective two, we create four categorical variables (low, medium, high and very high) to help us determine the level of renewable energy penetration at which countries achieve reliable power supply.

We specify the following models;

$$\text{logit}(\text{fragility} = 1) = \beta_0 + \beta_1(\text{medium}) + \beta_2(\text{high}) + \beta_3(\text{very high}) + \beta_4(\text{gdppc}) + \varepsilon_i \dots\dots\dots 6$$

$$\text{logit}(\text{fragility} = 1) = \beta_0 + \beta_1 \text{threshold}_x + \beta_2(\text{gdppc})_i + \varepsilon_i$$

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Within the production function, institutional quality I_i has its own elasticity θ . However, institutional quality may also enhance the marginal productivity of renewable inputs. Formally, we can allow the elasticity of renewable energy to depend on institutions:

$$\alpha_i = \alpha_0 + \alpha_1 I_i \dots\dots\dots 8$$

Substituting into the production function in equation 2

$$\ln R_i = \ln A_i + (\alpha_0 + \alpha_1 I_i) \ln RE_i + \beta \ln FFE_i + \gamma \ln K_i + \delta \ln L_i + \theta \ln I_i + \varepsilon_i$$

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Rearranging

$$\ln R_i = \ln A_i + (\alpha_0 + \alpha_1 I_i) \ln RE_i + \theta \ln I_i + \beta \ln FFE_i + \gamma \ln K_i + \delta \ln L_i + \varepsilon_i$$

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$$\ln R_i = \ln A_i + \alpha_0 I_i \ln RE_i + \alpha_1 I_i \ln RE_i + \theta \ln I_i + \beta \ln FFE_i + \gamma \ln K_i + \delta \ln L_i + \varepsilon_i$$

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From equation 10, α_1 now captures the elasticity of the interaction of institutional quality and renewable energy. We use electricity regulation to proxy institution quality in this model. Thus, the moderating effect of electricity regulation on the relationship between

renewable energy and power reliability is estimated using a basic ordinary least squares (OLS) regression:

$$\begin{aligned} \text{reliability} = & \beta_0 + \beta_1(RE) + \beta_2(ER) + \beta_3(RE * ER) + \beta_4(GDP\%PC) + \beta_5(URBAN) + \\ & \beta_6(POP_DEN) + \beta_7(FDI) + \beta_8(ENER_POV) + \\ & \varepsilon_i \dots\dots\dots 12 \end{aligned}$$

Estimation Techniques

To address the study objectives, this paper employed a combination of logistic regression, threshold analysis, and ordinary least squares estimation. For the first objective, which examines the relationship between renewable energy penetration and power sector fragility, a binary logistic regression model is used. Logistic regression is appropriate when the dependent variable is dichotomous and represents the probability of an event occurring. In this study, the dependent variable fragility takes the value 1 if a country's electricity system is classified as fragile and 0 otherwise. The logistic model estimates the probability that a country's power system falls into the fragile category as a function of renewable energy penetration and other control variables. The logit specification ensures that predicted probabilities lie within the [0,1] interval and allows coefficients to be interpreted in terms of odds ratios, which indicate how changes in explanatory variables affect the likelihood of system fragility.

To address the second objective, which investigates whether a threshold level of renewable penetration exists, the study employs two complementary strategies. First, renewable energy penetration is categorized into four groups (low, medium, high, and very high) to examine whether fragility probabilities differ across penetration levels. Second, a series of binary threshold variables is constructed at different renewable penetration levels (20%, 30%, 40%, 50%, and 60%) to identify potential nonlinear effects. These models test whether improvements in power reliability occur only after renewable penetration exceeds specific levels, consistent with absorptive capacity and infrastructure constraints in electricity systems.

The third objective evaluates whether electricity sector reforms moderate the relationship between renewable energy penetration and power reliability. Because the dependent variable for this objective is a continuous power reliability index, the analysis employs an ordinary least squares regression model with an interaction term. The interaction term captures the moderating role of electricity sector reforms. A statistically significant interaction coefficient indicates that the marginal effect of renewable energy penetration on power reliability depends on the strength of electricity regulation.

This study adopted a cross-sectional research design to examine the relationship between renewable energy penetration, electricity sector reforms, and power system reliability across Sub-Saharan Africa. A cross-sectional design was adopted because consistent longitudinal data on electricity regulation indicators and power reliability metrics are not available for many Sub-Saharan African countries over extended periods. In particular,

institutional indicators and reliability measures are often reported irregularly or only for selected years across different databases. Constructing a balanced panel dataset would therefore require substantial data imputation or would significantly reduce the number of countries included in the analysis. To preserve broad regional coverage and maintain data consistency across variables, the study relies on the most recent comparable observations available across countries.

Despite these advantages, cross-sectional analysis has several limitations that must be acknowledged. First, cross-sectional models do not capture temporal dynamics in renewable energy deployment, institutional reforms, or power system performance. As a result, the analysis cannot fully account for the timing of reforms or the lagged effects of renewable energy investments. Second, the cross-sectional framework limits the ability to establish causal relationships, as the estimated associations may reflect reverse causality or omitted variable bias. Third, country-level heterogeneity that evolves over time cannot be fully captured within a single-period framework. Nonetheless, cross-country comparisons remain valuable for identifying broad structural patterns and institutional conditions associated with power system fragility across the region. The cross-sectional design therefore provides a useful first step in examining the interaction between renewable energy penetration and electricity sector reforms in Sub-Saharan Africa.

Variable Description and Data Sources

The dependent variable used in the logistic regression analysis is fragility, a binary indicator reflecting the reliability performance of national electricity systems. The fragility indicator is constructed using firm-level electricity reliability indicators obtained from the World Bank Enterprise Surveys compiled by the World Bank. Two indicators are used: the percentage of firms experiencing electricity outages and the average number of power outages reported by firms in a typical month. These variables capture the reliability conditions of electricity supply from the perspective of economic agents operating within each country. Both indicators are standardized using z-score transformation and aggregated to construct a composite electricity reliability index for each country. Countries with composite scores above the sample threshold are classified as having fragile electricity systems (coded as 1), while those with lower scores are classified as relatively reliable (coded as 0).

Renewable energy penetration is measured as the percentage share of renewable sources in total electricity generation. Data for this variable are obtained from the International Renewable Energy Agency renewable electricity statistics database. Electricity sector reforms are captured using an electricity regulation index derived from the Grid Electricity Reform Index (GERI) compiled by the African Development Bank. The index evaluates the extent of electricity sector reforms across African countries, including regulatory independence, market liberalization, tariff reform, and institutional governance. Higher values of the index indicate stronger regulatory frameworks and more advanced reform

implementation. For the empirical analysis, the regulation index is mean-centered prior to constructing the interaction term with renewable electricity penetration.

Several control variables are included to account for structural differences across countries that may influence electricity reliability outcomes. GDP per capita is included as a proxy for economic development and infrastructure investment capacity. Urbanization rate captures the degree of demand concentration and the level of grid development. Population density reflects spatial demand patterns that may affect electricity transmission efficiency. Foreign direct investment represents external capital inflows that may support energy infrastructure expansion. Finally, energy poverty, measured as the proportion of the population lacking access to electricity, captures structural deficits in energy access that may influence overall system performance. Data for the control variables are obtained from the World Development Indicators maintained by the World Bank. Table 1 presents the definitions, measurements, and data sources for all variables used in the analysis.

Table 1: Variable Description

Variable	Description	Measurement	Source
Fragility	Power system fragility indicator derived from electricity reliability conditions	Binary variable (1 = fragile power system, 0 = reliable system) constructed from the composite electricity reliability index	Constructed by authors using World Bank Enterprise Survey
RenElec	Renewable electricity penetration	Share of renewable electricity output in total electricity generation (%)	World Bank World Development Indicators / IRENA
RenElec Categories	Renewable penetration levels used for threshold analysis	Low (<10%), Medium (10–30%), High (30–50%), Very High (>50%)	Constructed by authors
Threshold_X	Renewable penetration threshold variables	Binary indicators for renewable electricity shares $\geq 20\%$, $\geq 30\%$, $\geq 40\%$, $\geq 50\%$, and $\geq 60\%$	Constructed by authors
GDPpc	Economic development level	GDP per capita (constant USD)	World Bank World Development Indicators
Reliability	Power reliability composite index measuring electricity system stability	Continuous composite index capturing electricity system performance	World Economic Forum Energy Transition Index
ElecReg	Electricity sector regulation indicator	Electricity sector reform index derived from the Grid Electricity Reform Index	African Development Bank (AfDB)

Variable	Description	Measurement	Source
	capturing reform intensity	(GERI) and centered before estimation	
RenElec × ElecReg	Moderating variable	Interaction term between centered renewable electricity share and electricity regulation index	Constructed by authors
Urban	Urbanization level	Percentage of population living in urban areas	World Bank World Development Indicators
LnPopDensity	Population density	Natural logarithm of population density (people per square kilometer)	World Bank World Development Indicators
FDI	Foreign direct investment inflows	Net FDI inflows (% of GDP)	World Bank World Development Indicators
EnerPov	Energy poverty indicator	Share of population without access to electricity (%)	World Bank World Development Indicators
AccessElec	Electricity access rate	Percentage of population with access to electricity	World Bank World Development Indicators

Source: Compiled by Authors. continuous variables were centered to reduce multicollinearity

The dataset used in this study is cross-sectional. It consists of observations for 49 Sub-Saharan African countries, each representing the most recent available data points for key variables such as renewable electricity share, electricity regulation index, GDP per capita, and power reliability indicators. The data were compiled from multiple reputable international sources, including the World Bank World Development Indicators, International Renewable Energy Agency (IRENA), World Bank Enterprise Survey, and the African Development Bank's Energy Sector Database. Because several of these variables are not consistently reported annually for all countries, the analysis focuses on the most recent cross-sectional snapshot, allowing for comparison across countries rather than over time.

Results

Renewable Energy Penetration and Power Sector Fragility in Sub-Saharan Africa.

We start this section by presenting the findings for the first research question, which examines the relationship between power system fragility and renewable energy across 49 Sub-Saharan African (SSA) countries. A logistic regression model was estimated to identify

the relationship between renewable electricity share, income level (GDP per capita), and the likelihood of experiencing power fragility.

Table 2: Logistic Regression Results

Variable	Coefficient	Std. Error	z-value	P> z	[95% Conf. Interval]
ren_elec	0.00527	0.0094	0.56	0.575	-0.0131 to 0.0237
gdppc	-2.09511	0.91293	-2.29	0.022	-3.8844 to -0.3058
Constant	6.37893	3.01249	2.12	0.034	0.4746 to 12.2833
Number of observations = 49	Log likelihood = -29.80	Likelihood Ratio chi²(2) = 8.30 (p = 0.0157)	Pseudo R² = 0.1223	Pearson chi²(46) = 47.91 (p = 0.3951)	

Source: Compiled by Authors based on results from Stata 18

The logistic regression results presented in Table 2 examine the relationship between renewable electricity penetration and power sector fragility in Sub-Saharan Africa.

The coefficient on renewable electricity share (ren_elec) is positive ($\beta = 0.00527$) but statistically insignificant ($p = 0.575$), indicating that renewable energy penetration does not have a statistically meaningful effect on the likelihood of power sector fragility. In a logistic regression framework, this coefficient represents the change in the log-odds of fragility associated with a one-unit increase in renewable electricity share. Converting this to an odds ratio ($\exp(0.00527) \approx 1.0053$) suggests that a one percentage point increase in renewable electricity share is associated with approximately a 0.53% increase in the odds of fragility, although this effect is not statistically distinguishable from zero.

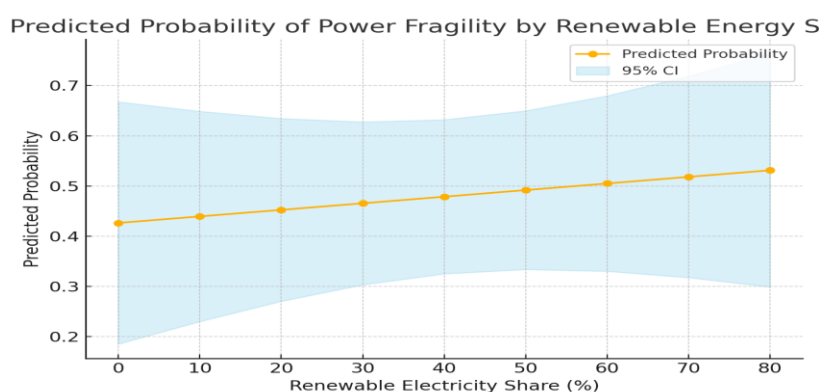
This finding implies that renewable energy expansion, in isolation, does not significantly improve power system reliability in the region. The positive sign, although insignificant, may reflect structural challenges such as intermittency, weak grid infrastructure, and limited storage capacity, which can constrain the effective integration of renewable energy into existing power systems.

In contrast, GDP per capita is found to be a statistically significant determinant of power fragility ($\beta = -2.095$, $p = 0.022$). The negative coefficient indicates that higher levels of economic development are associated with lower likelihood of fragility. Transforming the coefficient into an odds ratio ($\exp(-2.095) \approx 0.123$) shows that an increase in GDP per capita substantially reduces the odds of power fragility. Given that GDP per capita is specified in logarithmic form, this result implies that a proportional increase in income is associated with a significant decline in the probability of system fragility.

Substantively, this finding highlights the critical role of economic capacity in strengthening electricity systems through improved infrastructure investment, maintenance capacity, and institutional quality. It suggests that broader development conditions may be more

important than energy composition alone in determining reliability outcomes across Sub-Saharan Africa. With respect to model performance, the likelihood ratio chi-square statistic ($\chi^2 = 8.30$, $p = 0.0157$) indicates that the model is jointly significant. The pseudo- R^2 of 0.1223 suggests moderate explanatory power, which is typical for cross-sectional logistic regression models. The Pearson goodness-of-fit test ($p = 0.3951$) fails to reject the null hypothesis of good model fit, indicating no evidence of misspecification. Furthermore, the classification accuracy of approximately 63% suggests that the model has moderate predictive ability, with relatively balanced sensitivity and specificity.

Overall, given the focus of this paper on the impact of renewable energy on power stability in the SSA region, we further examine the marginal effects of renewable electricity on power fragility by looking closely at the predicted probabilities of power fragility. This is illustrated in Figure 1 and it shows the predicted probability of power fragility across different levels of renewable electricity share, while holding GDP per capita constant at its mean. The curve shows a mild upward trend, but the confidence intervals are wide and overlapping, indicating that the effect of renewable electricity on power fragility is not statistically significant.



Source: Compiled by Authors based on results from Stata 18

The result obtained from the empirical examination of objective one substantiates the complex dynamics shaping energy systems in Sub-Saharan Africa. At the moment, expanding renewable energy seem to be a key objective across the region, yet our analysis shows that it is not a statistically significant driver of power system fragility. In contrast, GDP per capita emerges as a robust determinant. This suggests that economic development remains a fundamental enabler of energy system resilience. This is through its influence on infrastructure investments, grid management capacity, and maintenance systems. From a policy perspective, these results imply that renewable energy programs in sub-Saharan Africa should be integrated with broader development strategies. Renewable

energy investments alone, without the supporting institutional and economic frameworks, may be insufficient to guarantee reliable and stable electricity systems.

Threshold Effects of Renewable Electricity Penetration on Power Sector Fragility

To further examine the relationship between renewable electricity penetration and power sector fragility, this study investigates potential non-linearities using categorical and threshold-based analyses. This approach is motivated by the possibility that the impact of renewable energy on power system performance may vary across different levels of penetration, particularly in contexts characterized by weak grid infrastructure and institutional constraints.

Table 3: Distribution by Renewable Energy Penetration Categories

Renewable Energy Category	Frequency	Percentage	Power Fragility Rate (%)	Countries with Reliable Supply
Low (<10%)	16	32.65	37.50	10 (62.50%)
Medium (10-30%)	7	14.29	57.14	3 (42.86%)
High (30-50%)	6	12.24	16.67	5 (83.33%)
Very High (50%+)	20	40.82	65.00	7 (35.00%)
Total	49	100.00	48.98	25 (51.02%)

Note: Power fragility rate represents the percentage of countries in each category experiencing unreliable power supply

Source: Compiled by Authors based on results from Stata 18

Table 3 presents the distribution of Sub-Saharan African countries across renewable energy penetration categories, along with corresponding fragility rates. The descriptive evidence reveals clear heterogeneity in outcomes across categories. Countries in the high penetration category (30–50%) exhibit the lowest fragility rate (16.67%), with 83.33% of countries in this group maintaining reliable power supply. In contrast, countries in the very high penetration category (>50%) record the highest fragility rate (65%), despite having the largest number of countries. Similarly, the medium penetration category (10–30%) shows a relatively high fragility rate (57.14%), while the low penetration group (<10%) exhibits a moderate fragility rate (37.5%).

These patterns provide preliminary evidence of a non-linear relationship between renewable energy penetration and power sector fragility. Specifically, reliability appears to improve at intermediate levels of renewable penetration but deteriorate at very high levels, suggesting the presence of system integration constraints at higher shares of renewables.

Table 4: Logistic Regression Results – Renewable Energy Categories and Power Fragility

Variable	Coefficient	Std. Error	z-value	p-value	Odds Ratio	95% CI
Medium (10-30%) vs Low	1.404	1.058	1.33	0.185	4.07	[0.51, 32.41]
High (30-50%) vs Low	-1.436	1.298	-1.11	0.269	0.24	[0.02, 3.03]
Very High (50%+) vs Low	0.730	0.769	0.95	0.342	2.07	[0.46, 9.36]
GDP per capita	-2.574	1.050	-2.45	0.014	0.08	[0.01, 0.60]
Constant	7.739	3.331	2.32	0.020	2297.08	[3.35, 1,573,141]
N = 49		LR χ^2 = 13.57, p = 0.009		Pseudo R ² = 0.1999		

Source: Compiled by Authors based on results from Stata 18

To formally test these patterns, Table 4 reports logistic regression estimates using renewable energy categories, with the low penetration group as the reference category. The results indicate that none of the categorical coefficients are statistically significant at conventional levels. However, the direction and magnitude of the coefficients provide important insights. Countries in the medium penetration category exhibit higher odds of fragility (odds ratio = 4.07), while those in the high penetration category (30–50%) show substantially lower odds (odds ratio = 0.24). In contrast, the very high penetration category is associated with higher odds of fragility (odds ratio = 2.07).

Although these effects are not statistically significant, the pattern of coefficients is consistent with the descriptive evidence and supports the presence of a non-linear relationship between renewable energy penetration and power fragility. As in the baseline model, GDP per capita remains a strong and statistically significant determinant of fragility ($p = 0.014$), reinforcing the importance of economic development in shaping power system outcomes.

Table 5: Predicted Probabilities of Power Fragility by Renewable Energy Category

Renewable Energy Category	Predicted Probability	Standard Error	95% Confidence Interval
Low (<10%)	0.386	0.139	[0.115, 0.658]
Medium (10-30%)	0.719	0.174	[0.379, 1.060]
High (30-50%)	0.130	0.133	[-0.130, 0.390]
Very High (50%+)	0.566	0.126	[0.319, 0.814]

Source: Compiled by Authors based on results from Stata 18

Further insights are obtained from the predicted probabilities reported in Table 5. The probability of fragility is highest for countries in the medium category (0.719) and lowest for those in the high penetration category (0.130). Countries in the very high category also

exhibit relatively high fragility probability (0.566). These results reinforce the conclusion that moderate levels of renewable penetration (30–50%) are associated with the most favorable reliability outcomes, while both low and very high levels are associated with higher fragility risks.

Table 6: Pairwise Statistical Comparisons Between Renewable Energy Categories

Comparison	Chi-square	p-value	Significance Level
Medium vs Low	1.76	0.185	Not significant
High vs Low	1.22	0.269	Not significant
Very High vs Low	0.90	0.342	Not significant
High vs Medium	3.61	0.058	Marginally significant
Very High vs High	2.96	0.085	Marginally significant
Joint test (all categories)	4.61	0.203	Not significant

Source: Compiled by Authors based on results from Stata 18

The pairwise comparisons presented in Table 6 show that differences across categories are generally not statistically significant, although some comparisons, particularly between the high and medium categories ($p = 0.058$) are marginally significant. This suggests that while the overall pattern is economically meaningful, statistical power may be limited due to the relatively small sample size.

Table 7: Threshold Model Comparison

Threshold Model	Coefficient	Std. Error	p-value	Log Likelihood	Pseudo R ²	Model Significance
20% threshold	0.244	0.648	0.706	-29.889	0.1197	$p = 0.017$
30% threshold	-0.113	0.651	0.862	-29.944	0.1181	$p = 0.018$
40% threshold	-0.075	0.662	0.910	-29.953	0.1178	$p = 0.018$
50% threshold	0.693	0.651	0.287	-29.391	0.1344	$p = 0.010$
60% threshold	0.532	0.674	0.430	-29.647	0.1268	$p = 0.014$

Source: Compiled by Authors based on results from Stata 18. Coefficients represent the effect of being above the threshold.

To further explore threshold effects, Table 7 presents results from alternative threshold specifications. Among the tested thresholds (20%, 30%, 40%, 50%, and 60%), the 50% threshold provides the best model fit, as indicated by the highest pseudo-R² (0.1344) and strongest overall model significance ($p = 0.010$). This suggests that renewable energy penetration beyond 50% may represent a critical point at which system fragility increases, likely due to grid instability, intermittency, and insufficient balancing capacity.

Overall, the findings from the threshold analysis provide consistent evidence that the relationship between renewable energy penetration and power sector fragility in Sub-Saharan Africa is non-linear. While moderate levels of renewable energy penetration are

associated with improved reliability, very high levels may exacerbate fragility in the absence of adequate infrastructure, storage capacity, and regulatory support.

Electricity Sector Reforms, Renewable Energy Penetration and Power Sector Reliability

To address the third objective, this study examines whether electricity sector reforms moderate the relationship between renewable energy penetration and power sector reliability. The analysis proceeds in two stages: first, a baseline model estimating the independent effects of renewable energy and reforms; and second, an interaction model capturing the moderating effect.

Table 8: Baseline Ordinary Least Square Regression Result

Variable	Coefficient	Std. Error	z-value	P> z	95% Confidence Interval
ren_elec_c	0.0009	0.0077	0.12	0.907	[-0.0147, 0.0165]
elec_reg_c	1.2962	0.9313	1.39	0.171	[-0.5846, 3.1770]
gdppc	-0.9751	1.0525	-0.93	0.360	[-3.1006, 1.1505]
urban	0.0229	0.0197	1.17	0.250	[-0.0168, 0.0626]
ln_pop_density	-0.1748	0.2396	-0.73	0.470	[-0.6587, 0.3090]
fdi	-0.0935	0.0617	-1.52	0.137	[-0.2181, 0.0310]
ener_pov	0.0263	0.0171	1.53	0.133	[-0.0083, 0.0609]
_cons	1.8355	4.5287	0.41	0.687	[-7.3104, 10.9814]
	N = 49	Prob > F = 0.0188	Adj. R-squared = 0.2051	R-squared = 0.3211	Root MSE = 1.5555

Source: Compiled by Authors based on results from Stata 18

Table 8 presents the baseline Ordinary Least Squares (OLS) estimates. The results indicate that neither renewable electricity penetration ($\beta = 0.0009$, $p = 0.907$) nor electricity sector reforms ($\beta = 1.2962$, $p = 0.171$) exert a statistically significant independent effect on power sector reliability. This suggests that, when considered in isolation, neither increased renewable energy share nor improvements in regulatory frameworks are sufficient to significantly influence reliability outcomes across Sub-Saharan Africa. Similarly, the control variables; GDP per capita, urbanization, population density, and foreign direct investment, are not statistically significant in this specification. Although the model is jointly significant (Prob > F = 0.0188), the relatively modest explanatory power ($R^2 = 0.3211$) indicates that important interaction effects may be omitted.

To account for this possibility, Table 9 introduces an interaction term between renewable electricity penetration and electricity sector reforms. The results show a marked improvement in model performance, with R^2 increasing to 0.4153 and the overall model significance strengthening (Prob > F = 0.0034). Most importantly, the interaction term ($\beta =$

-0.0720, $p = 0.015$) is negative and statistically significant, providing strong evidence of a moderating effect.

Table 9: Ordinary Least Square Regression with moderation Effects

Variable	Coefficient	Std. Error	z-value	P> z	95% Confidence Interval
ren_elec_c	0.0060	0.0075	0.80	0.430	[-0.0092, 0.0213]
elec_reg_c	-0.0964	1.0326	-0.09	0.926	[-2.1834, 1.9906]
ren_reform_int	-0.0720	0.0284	-2.54	0.015	[-0.1294, -0.0147]
gdppc	-0.2204	1.0325	-0.21	0.832	[-2.3071, 1.8664]
urban	0.0166	0.0186	0.89	0.378	[-0.0210, 0.0543]
ln_pop_density	-0.1020	0.2269	-0.45	0.655	[-0.5606, 0.3566]
fdi	-0.1014	0.0580	-1.75	0.088	[-0.2187, 0.0158]
ener_pov	0.0341	0.0164	2.08	0.044	[0.0010, 0.0673]
constant	-0.6569	4.3665	-0.15	0.881	[-9.4818, 8.1681]
	N = 49,	R-squared = 0.4153	Adj. R-squared = 0.2984	, Prob > F = 0.0034,	Root MSE = 1.4614

Source: Compiled by Authors based on results from Stata 18

The negative coefficient on the interaction term implies that the impact of renewable electricity on power reliability becomes more favorable as the level of electricity sector reform increases. In other words, renewable energy penetration, which is not significant on its own, contributes to improved reliability only in countries with stronger regulatory and institutional frameworks. This finding directly supports the study's central hypothesis that institutional quality conditions the effectiveness of renewable energy deployment.

Notably, energy poverty emerges as a positive and statistically significant determinant of power fragility in the interaction model ($\beta = 0.0341$, $p = 0.044$), indicating that higher levels of energy deprivation are associated with weaker reliability outcomes. This highlights the structural constraints facing energy systems in the region and reinforces the importance of inclusive energy policies.

To further interpret the moderation effect, Table 10 reports the marginal effects of renewable electricity penetration at different levels of electricity sector reform. The results reveal a clear pattern. At low levels of reform (-0.3), renewable electricity increases fragility (marginal effect = 0.028), suggesting that weak institutional environments are unable to effectively integrate renewable energy into the grid. At average reform levels, the effect is negligible (0.006), indicating limited impact. However, at high levels of reform ($+0.3$), renewable electricity significantly reduces fragility (marginal effect = -0.016), implying that strong regulatory frameworks enable renewable energy to enhance power system reliability.

Table 10: Marginal Effects of renewable electricity access at varying reform levels

Reform Level	Marginal Effect of ren_elec_c
Low reforms (-0.3)	0.028
Average (0)	0.006
High reforms (+0.3)	-0.016

Source: Compiled by Authors based on results from Stata 18

Taken together, these findings provide robust evidence that the relationship between renewable energy and power reliability in Sub-Saharan Africa is conditional rather than direct. Renewable energy alone does not guarantee improved electricity outcomes; its effectiveness depends critically on the presence of supportive institutional and regulatory environments. Thus, this study's findings buttress the importance of aligning renewable energy expansion with comprehensive electricity sector reforms to achieve reliable and sustainable power systems.

Discussion of Results

This study contributes to the growing empirical literature on energy transitions and electricity sector performance in Sub-Saharan Africa by examining the joint role of renewable energy penetration and electricity sector reforms in shaping power system reliability. The findings both align with and extend existing evidence in several important ways.

First, the result that GDP per capita is a strong and significant predictor of reduced power sector fragility is consistent with the broader empirical literature linking economic development to infrastructure quality and service reliability. Cross-country studies such as Calderón and Servén (2010) show that higher-income economies tend to exhibit better infrastructure outcomes due to greater fiscal capacity, stronger institutions, and improved maintenance systems. Similarly, Eberhard et al. (2017) highlight that financially viable power sectors, often associated with higher-income countries are better able to sustain reliable electricity supply. The present findings reinforce this argument by demonstrating that, within Sub-Saharan Africa, economic development appears to dominate renewable energy penetration as a determinant of reliability. This suggests that energy system performance is fundamentally embedded within broader structural and macroeconomic conditions.

However, the finding that renewable energy penetration is not a statistically significant independent predictor of power reliability contrasts with strands of the literature that emphasize its positive contributions to energy security and system resilience (Bhattacharya et al., 2016; Apergis & Payne, 2014). A key distinction lies in the outcome variable: while much of the existing literature focuses on growth, emissions, or energy access, relatively fewer studies examine reliability as a performance metric. In line with Bazilian et al. (2012)

and Pueyo (2018), the results here suggest that in weak grid environments, renewable energy integration may introduce technical and operational challenges; such as intermittency and grid instability, that offset its potential benefits. This helps explain the mixed empirical evidence and highlights the importance of context-specific constraints in Sub-Saharan Africa.

Second, the evidence of a non-linear relationship between renewable energy penetration and power fragility provides an important refinement to the literature on energy mix and system performance. While prior studies have generally treated renewable energy as a monotonic contributor to improved outcomes, the findings here suggest that the relationship is conditional on the level of penetration. The observed pattern here where moderate renewable penetration (30–50%) is associated with the lowest fragility, aligns with emerging evidence that system balance and diversification are critical for grid stability. Moner-Girona et al. (2016) and Trotter (2016) emphasize the importance of hybrid and decentralized energy systems in African contexts, while overly rapid or uncoordinated renewable expansion may strain existing infrastructure. The increase in fragility observed at very high levels of renewable penetration is consistent with concerns in the literature regarding integration constraints in systems lacking adequate storage, transmission capacity, and flexibility mechanisms. Thus, this study extends existing work by providing empirical support for a threshold-based interpretation of renewable energy impacts in developing country electricity systems.

Third, and most importantly, the finding that electricity sector reforms significantly moderate the renewable energy–reliability relationship represents a key contribution to the literature. While previous studies have examined the independent effects of reforms on efficiency and access (Jamasb et al., 2015; Sen & Jamasb, 2012), relatively few have explicitly analyzed how institutional quality conditions the effectiveness of renewable energy deployment. The negative and statistically significant interaction effect observed in this study indicates that renewable energy improves reliability only in the presence of strong regulatory frameworks. This is consistent with the institutional literature, which emphasizes that infrastructure outcomes depend critically on governance quality, regulatory credibility, and policy coherence (Calderón & Servén, 2010).

Moreover, this finding aligns with evidence from reform experiences in Africa, where countries with more advanced regulatory structures; such as independent regulators and transparent market frameworks have achieved better electricity sector outcomes (Eberhard et al., 2017). At the same time, it extends the literature by demonstrating that weak or incomplete reforms may not only fail to enhance performance but may actively undermine the benefits of renewable energy expansion. This helps reconcile conflicting empirical findings and underscores the importance of considering interaction effects rather than isolated policy interventions.

Policy Implications of Findings

The findings of this study point to the need for more targeted and coordinated policy interventions to improve power sector reliability in Sub-Saharan Africa. First, given the strong role of economic development, governments should prioritize investments that strengthen the financial and operational viability of the power sector. This includes expanding public investment in transmission and distribution infrastructure, improving utility cost recovery through reforms, and enhancing maintenance systems. Evidence from African power sector reforms suggests that financially sustainable utilities are better able to deliver reliable electricity services (Eberhard et al., 2017).

Second, the results highlight that renewable energy expansion must be accompanied by robust and credible regulatory frameworks. Policymakers should focus on strengthening independent electricity regulatory agencies, ensuring regulatory autonomy, transparency, and enforcement capacity. In addition, implementing competitive procurement mechanisms, such as renewable energy auctions, has been shown to reduce costs and improve project delivery in countries such as South Africa and Morocco. Clear grid codes, standardized power purchase agreements, and transparent licensing processes are also essential to support effective renewable integration.

Third, the non-linear relationship between renewable energy penetration and reliability suggests that policymakers should adopt a system-balancing approach rather than pursuing aggressive renewable targets in isolation. This includes investing in grid flexibility measures, such as energy storage systems, smart grid technologies, and flexible generation capacity, to manage intermittency. Integrated resource planning frameworks should be used to align renewable expansion with transmission capacity and demand growth.

Finally, the results emphasize the importance of addressing structural constraints such as energy poverty. Policies aimed at expanding access such as targeted subsidies, decentralized mini-grid programs, and pay-as-you-go solar systems should be complemented with broader institutional reforms to ensure that access translates into reliable and sustainable energy use.

Conclusion

This study examined the relationship between renewable energy penetration, electricity sector reforms, and power sector reliability across 49 Sub-Saharan African countries. Using a combination of logistic regression, threshold analysis, and moderated OLS estimation, the study provides new empirical evidence on the conditions under which renewable energy contributes to reliable electricity systems in developing economies.

The findings reveal that renewable energy penetration, when considered in isolation, is not a statistically significant determinant of power sector fragility. Instead, GDP per capita emerges as a robust predictor, highlighting the central role of economic development in shaping electricity system performance. This underscores the importance of structural and

macroeconomic conditions in determining the reliability of power infrastructure in Sub-Saharan Africa. Further analysis shows that the relationship between renewable energy and power reliability is non-linear. Countries with moderate levels of renewable energy penetration; approximately 30 to 50 percent, exhibit the lowest levels of power fragility, while both low and very high levels of penetration are associated with weaker reliability outcomes. This finding suggests that a balanced and well-integrated energy mix is more effective than uncoordinated expansion of renewable capacity.

Most importantly, the study demonstrates that electricity sector reforms play a critical moderating role. The results indicate that renewable energy improves power reliability only in countries with stronger regulatory and institutional frameworks. In weak reform environments, renewable energy expansion may fail to deliver reliability gains and may even exacerbate system instability. This highlights the importance of institutional quality as a key enabling condition for successful energy transitions.

Taken together, the findings contribute to the literature by showing that the effectiveness of renewable energy in improving electricity reliability is not automatic but conditional on economic capacity and institutional strength. The study therefore advances a more integrated perspective in which technological change, institutional reform, and economic development jointly determine energy sector outcomes. From a policy standpoint, the results suggest that renewable energy strategies in Sub-Saharan Africa should be complemented by comprehensive electricity sector reforms, including strengthening regulatory institutions, improving grid infrastructure, and implementing cost-reflective tariff systems. Without such complementary measures, the potential benefits of renewable energy may not be fully realized.

Notwithstanding these contributions, the study is subject to several limitations. The use of a cross-sectional design constrains the ability to establish causal relationships and does not capture temporal dynamics in energy transitions. In addition, data limitations restrict the analysis to available indicators, which may not fully reflect all dimensions of electricity reliability and institutional quality. Future research could extend this analysis using panel data approaches to examine dynamic effects over time, as well as incorporate more granular measures of grid performance and reform implementation.

In conclusion, achieving reliable and sustainable electricity systems in Sub-Saharan Africa requires more than expanding renewable energy capacity. It demands a coordinated approach that aligns energy investments with institutional reform and broader economic development. Only through such an integrated strategy can the region effectively bridge its power gap and support long-term development objectives.

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