



Green Innovation and Energy Poverty in Sub-Saharan Africa: Institutional, Structural, and Climatic Pathways

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Abstract. The study analyses the impact of green innovation (GINV) on energy poverty across 43 sub-Saharan African (SSA) economies spanning the period 2002–2024, taking into account the moderating influences of institutional quality and vulnerability on climate change. GINV is proxied by the consumption of renewable energy, while electricity access and access to clean cooking fuels are used to proxy energy poverty. Using fixed-effects estimation with Driscoll–Kraay standard errors (DK-PE) and panel-corrected standard errors (PCSE) for robustness, the findings show that GINV has a positive but statistically insignificant average effect on electricity access, whereas climate change vulnerability significantly reduces electricity access. Institutional quality does not robustly moderate the GINV – energy poverty relationship, while the interaction between GINV and climate vulnerability is positive and significant, indicating that green innovation becomes more effective in improving electricity access under higher climate-related risks. Evidence of a nonlinear relationship further shows that higher renewable energy shares strengthen the positive effect of GINV on electricity access. These findings suggest that renewable energy deployment alone may not be sufficient to reduce energy poverty in SSA, highlighting the need for context-specific renewable energy policies, climate-resilient energy infrastructure, and stronger energy-sector institutions.

Keywords: energy poverty, green innovation, institutional quality, climate vulnerability, sub-Saharan Africa

JEL Classification: O13, O55, P48, Q42, Q54

1. Introduction

Access to clean, affordable, reliable, and sustainable energy services plays a crucial role in driving economic development, social welfare, and the broader Sustainable Development Goals (SDGs). While energy access has improved over time globally, energy poverty remains widespread in SSA. More than two-thirds of SSA's population still have no access to electricity, and around 780 million people rely on polluting solid fuels for cooking (International Energy Agency, 2022). Chronic energy poverty undermines economic productivity and opportunity, limits human health and well-being, exacerbates inequality, and constrains social inclusion (Igawa and Managi, 2022; Piwowar, 2021; Shahzad et al., 2022; Ogede, Oduola, and Onanuga, 2023). These impacts persist amid widespread exposure to climate-related shocks, which can damage energy infrastructure, heighten investment risks, and derail energy transition efforts (Jacolin and Debels-Lamblin, 2020; Azubuike et al., 2025; Kilungo et al., 2025).

Against this backdrop, green innovation has received growing attention in academic and policy debates as an important driver of sustainable energy transitions and energy poverty alleviation. Conceptually, green innovation should reduce energy poverty through several macroeconomic channels. By lowering the cost and increasing the attractiveness of renewable energy technology and infrastructure deployment and diffusion, improving energy efficiency, and enabling decentralized electricity systems, green innovation expands access to clean and modern energy services while reducing reliance on fossil fuels. Consistent with this mechanism, most studies find that green innovation helps improve energy access and reduce energy poverty worldwide (Hossain et al., 2025; Lee et al., 2022; Wei et al., 2024; Zhang and Yu, 2024). However, green innovation is unlikely to exert similar effects on energy poverty across all countries because it operates within broader institutional and environmental frameworks that can either strengthen or weaken its effects.

Institutions are one of the primary avenues through which green innovation may translate into energy transition outcomes. By promoting sound governance practices, institutions support better policy quality, implementation effectiveness, investment certainty, and clean energy technology diffusion (Nguyen and Su, 2022; Thuy and Hoang, 2023). As such, countries with higher institutional quality are expected to benefit more from green innovation and experience better green innovation–poverty pathways. Conversely, climate vulnerability could weaken institutional capacities to facilitate green-innovation-led energy transitions through multiple channels. Climatic shocks could directly damage energy infrastructure, undermine investor confidence, disrupt renewable energy deployment, and reduce energy access and affordability. Although the vast majority of studies find that climate vulnerability hampers green innovation (Liu et al., 2024; Xiao and Fei,

2024), others suggest a positive effect of climate vulnerability on green innovation based partly on the premise that rising climate risks and climate disasters could incentivize innovation and investment towards cleaner energy systems (Ren et al., 2024; Zhen et al., 2025). As such, these findings suggest that climate vulnerability may moderate rather than determine green innovation impacts on energy poverty.

While there is growing evidence on the pathways through which green innovation can alleviate energy poverty, important gaps remain in the literature. First, extant studies are heavily concentrated in China and select emerging economies while providing relatively scant evidence on the role of green innovation in energy transitions in SSA. Differences in energy systems, institutional capacities, and climatic conditions between SSA and other regions suggest that the green innovation effects reported in prior studies may not extrapolate to SSA. Second, extant studies generally estimate unconditional effects of green innovation without considering the institutional environment and climate conditions under which green innovation could have differential effects on energy poverty. Third, while institutional quality and climate vulnerability are independently linked to energy transition outcomes, little is known about their conditional roles in influencing the relationship between green innovation and energy poverty. Filling these gaps is especially important for SSA countries due to the prevalence of energy poverty and weak institutions alongside high exposure to climate shocks.

Nevertheless, to address these gaps, this study investigates the effect of green innovation on energy poverty across 43 SSA countries. In doing so, the study examines whether institutional quality and climate vulnerability moderate the green innovation – energy poverty nexus. Modelling institutional quality and climate vulnerability jointly within a unified framework allows this study to provide new evidence on contexts in which green innovation can accelerate improved energy access in SSA. The paper contributes to existing literature in four ways. First, it provides region-wide evidence on the green innovation and energy poverty relationship for SSA, which remains underrepresented in the literature. Second, it builds on prior research by theorizing and empirically examining the roles of institutional quality and climate vulnerability as moderators of green innovation rather than treating them as independent drivers of energy poverty. Third, this study estimates models using fixed effects with DK-FE as well as PCSE to account for both cross-sectional dependence and heterogeneity and serial correlation. Fourth, the study provides practical insights into how institutional quality and climate vulnerability condition the relationship between green innovation and energy poverty in SSA, which could help design resilient and inclusive energy transition strategies.

The remainder of the paper proceeds as follows. Section 2 reviews relevant literature on the green innovation – energy poverty nexus. Section 3 describes data sources and variables, theorizes expectations, and details the empirical strategy.

Empirical results are reported and discussed in Section 4. Section 5 concludes with implications for policymakers.

2. Review of Empirical Literature

2.1. Green Innovation and Energy Poverty

These mechanisms suggest that green innovation should reduce energy poverty. By stimulating the deployment of renewables and clean energy, enhancing energy efficiency, and expanding access to modern energy infrastructure, GINV decreases the cost of providing energy services, enables decentralized electricity provision, and increases the availability, affordability, and reliability of electricity services, especially in underprivileged communities. Evidence supports several of these proposed mechanisms. Studies generally find that green innovation alleviates electricity shortage and contributes to reductions in energy poverty via the increased adoption of renewables, technological advancement, and improvements in energy efficiency (Amer and Kareem, 2025; Batool et al., 2022; Hossain et al., 2025; Lee et al., 2022; Wei et al., 2024; Wu et al., 2024; Zhang and Yu, 2024). Moreover, existing research shows that green innovation has a more substantial impact where energy poverty is more pronounced, possibly because decentralized renewable energy systems can help bypass infrastructural barriers. Complementarities in structural factors could nevertheless enable or inhibit green innovation from reducing energy poverty. Studies show that the positive effect of green innovation is stronger when the provision of energy infrastructure is more developed, governments are more effective, and policy environments are more conducive to innovation. Industrial distortions, premature urbanization, poor infrastructure, and climate risks can weaken the relationship between green innovation and energy poverty reduction (Lee et al., 2022; Varo et al., 2022; Wei et al., 2024; Zhang and Yu, 2024). There are several gaps in our understanding of how GINV affects energy poverty. First, empirical analysis is limited to China and a few developing economies, with little analysis of sub-Saharan Africa. Second, prior research estimates an average effect without considering how governance, market mechanisms, and climate vulnerability may influence the effectiveness of green innovation. Third, no studies are found to investigate if climate vulnerability moderates the impact of green innovation on energy poverty. This study aims to fill these gaps.

2.2. Institutional Quality and Energy Poverty

Institutional quality can facilitate green-technology-induced progress in access to electricity, enables investments in energy infrastructure by public and private

actors, allows better energy services provision, and encourages more rapid diffusion of renewable energy technologies. As a result, institutional quality should bolster the effectiveness of green innovation in alleviating energy poverty. Support for this mechanism abounds in extant empirical research. Better governance has been shown to reduce energy poverty through improvements in electricity access infrastructure, public investment activity, institutional quality, and financial capital investments (Bazilian et al., 2014; Certomà et al., 2023; Kwiliński et al., 2024; Nguyen and Su, 2022; Thuy and Hoang, 2023).

Recent research has additionally shown governance to increase the effectiveness of government expenditure, international financial aid, and digital governance projects in tackling energy poverty (Feng et al., 2025; Liu et al., 2025; Xin et al., 2024). However, recent research highlights that these relationships are not always linear. Threshold effects have been documented in the governance – energy access relationship, showing that improvements in institutional quality decrease energy poverty significantly only after governance surpasses a minimum threshold (Mawutor et al., 2023). Despite this evidence, few studies explore institutional quality as a moderator of the green innovation – energy poverty relationship. This statement holds especially true in the context of sub-Saharan Africa. As such, the conditional effects of governance are not well understood.

2.3. Climate Vulnerability and Green Innovation

Climate vulnerability is another policy-relevant moderating factor that imposes structural constraints on green innovation activities. Climate disasters, heatwaves, floods, and droughts destroy energy supply facilities, discourage investments by increasing risk perceptions, and dampen the incentives to develop new technologies (Barkat-Somo et al., 2021). Therefore, energy access may benefit less from green innovation when climate vulnerability is high. Climate vulnerability appears to lower green innovation through increasing uncertainty, restricting investment activity, and hampering technological advancement (He et al., 2024; Lee et al., 2025; Liu et al., 2024; Niu et al., 2023; Wang and Liu, 2024; Wu, 2025; Xiao and Fei, 2024).

However, there are also studies reporting that worsening climate risks motivate innovation by driving firms' and governments' investments towards cleaner production methods and climate adaptation measures (Lyu, 2025; Ren et al., 2024; Zhen et al., 2025). These conflicting findings imply that climate vulnerability can affect the quality of green innovation, rather than merely its quantity. While studies on this topic are rapidly growing, three gaps remain. First, existing evidence comes almost exclusively from China, BRICS countries, or global samples, and Africa remains largely understudied. Second, prior literature primarily focuses on the direct effects of climate vulnerability and overlooks how its interaction with

green innovation may affect energy access. Third, potential nonlinear effects and cross-regional heterogeneity have not been examined. These three gaps motivate the inclusion of climate vulnerability as a moderator in this study.

2.4. Summary of Research Gaps

Existing literature recognizes green innovation as an effective tool for energy poverty alleviation while acknowledging the roles of institutional quality and climate vulnerability affecting energy transitions. However, there remain three gaps in the literature. First, empirical studies on energy transitions focus mostly on China and few emerging economies leaving sparse evidence on SSA. Second, existing studies provide estimations of mean effects while failing to consider how institutional quality and climate vulnerability moderate green innovation effectiveness. Third, limited studies consider green innovation, institutional quality, and climate vulnerability simultaneously in a single empirical framework. Hence, addressing these gaps will allow a more comprehensive examination of the circumstances under which green innovation effectively reduces energy poverty in sub-Saharan Africa.

3. Methodology

3.1. Data and Sample Selection

The study uses unbalanced panel data of 43 SSA countries for the period 2002–2024. SSA was chosen because it has the highest prevalence of energy poverty worldwide, marked by poor access to electricity services, fragmented energy markets and infrastructure, low institutional capacity, and vulnerability to climate change and natural disasters. Simultaneously, the SSA region has experienced a growing renewable energy uptake and decentralized electricity solutions over recent years, thus providing a relevant landscape to analyse the green innovation – energy poverty nexus. Data come from publicly available and reputable sources, including the World Development Indicators (WDI), the Worldwide Governance Indicators (WGI), and the Global Data Lab (GDL). *Table 1* outlines the variables, measurements, and data sources used in this study.

The dependent variable is energy poverty, measured by access to electricity (% of the population) following Ogede et al. (2024). Access to electricity is employed as a proxy for energy poverty because despite energy poverty being multi-dimensional – across the domains of affordability, reliability, clean cooking technologies, and quality of energy service – data availability limits most cross-country energy poverty studies to use electricity access as their outcome variable. Therefore,

the findings of this study should be viewed as informing about electricity access as a dimension of energy poverty, and not energy poverty in its entirety. The main explanatory variable is green innovation, proxied by renewable energy consumption, obtained by the share of renewable energy in total final energy consumption (%) following Nchofoung et al. (2024). At the macrolevel, an increased uptake and use of renewable energy technologies can be seen to reflect green-innovation diffusion across a country's energy system. As such, renewable energy consumption can serve as a suitable proxy measure for green innovation because it informs on the adoption and widespread utilization of green energy technologies and does not measure firm-level innovation outputs such as patents or licences. Green innovation is expected to reduce energy poverty by supporting decentralized electricity systems, improving energy efficiency, and broadening electricity access through clean energy sources. The moderating variables are institutional quality (IQ) and climate vulnerability (CVI). Institutional quality is measured using a PCA-generated index composed of six Worldwide Governance Indicators (control of corruption, rule of law, regulatory quality, government effectiveness, political stability, and absence of violence/threats, voice, and accountability) following Olaniyi and Oladeji (2020), Ogede, Siyanbola, Adegboyega et al. (2023), and Ogede, Oduola, and Tihamiyu (2024). Climate vulnerability is proxied using the Global Data Lab Vulnerability Index following Smits and Huisman (2024). Robust institutional quality is hypothesised to support policy implementation and foster investment incentives to green innovation efforts in extending energy access (Haldar et al., 2023).

Control variables include GDP per capita growth rate to account for economic performance and foreign direct investment (FDI). Gross domestic product (GDP) growth represents overall economic growth and may affect electricity access by providing households with income needed to pay for energy services and enable governments to invest in energy infrastructure (Apergis and Payne, 2012; Sadorsky, 2010). FDI may support energy access by supporting technology transfers and infrastructure roll-out across sectors; however, its contributions are sectoral and conditioned on institutional quality (Alfaro et al., 2004; Omri and Kahouli, 2014). The study also motivates urbanization, industrialization, population growth, and energy prices as potential control factors. *Table 1* presents the summary of the variable, description, and sources.

Table 1. *Summary of the variables, description and sources*

Variables	Measurement/Description	Source
Energy Poverty (EP)	Access to electricity (% of population)	WDI
Economic growth (GDPpcg)	GDP per capita (constant 2015 US\$)	WDI
Urbanization (URB)	Urban population (% of total population)	WDI

Variables	Measurement/Description	Source
Green Innovation (GINV)	% of renewable energy consumption	WDI
Population (POP)	Population growth (annual %)	WDI
Economic growth	GDP per capita growth rate	WDI
Foreign direct investment	Ratio of FDI to GDP	WDI
Institutional quality (IQ)	PCA of CC, GE, PS, RQ, RL, VA	Authors' compilation
Control of Corruption (CC)	Control of Corruption – Governance estimate	WGI
Government Effectiveness (GE)	Government Effectiveness – Governance estimate	WGI
Political Stability (PS)	Political Stability – Governance estimate	WGI
Regulatory Quality (RQ)	Regulatory Quality – Governance estimate	WGI
Rule of Law (RL)	Rule of Law – Governance estimate	WGI
Voice and Accountability (VA)	Voice and Accountability – Governance estimate	WGI

3.2. Model and Theoretical Framework

To begin with, this study is primarily based on technological innovation systems (TIS) theory, institutional theory, and energy poverty literature. The TIS approach states that the creation and adoption of new technologies is dependent on interactions between institutions, capital markets, and financial structures (Branscomb et al., 2002). Thus, technology alone might not be sufficient to lead innovation processes such as energy transitions. From a technological innovation systems perspective, literature shows that deployment patterns within Africa cannot be attributed to technological advancements in electricity provision systems but instead both supply-side and demand-side innovations are required to achieve energy access on a larger scale (Agbemabiese et al., 2012). Institutional theory also recognizes that government effectiveness, regulatory quality, and policy uncertainty determine technological and economic performance. Institutions can determine who has the incentives to undertake investments and make improvements on innovation capacity and infrastructure development among other economic processes within energy systems. As with other developing countries, weak regulatory capabilities and policy uncertainty determine the pace with which renewable energy sources diffuse and innovation policies will be effective in African countries. For example, strong institutions can create room for better regulatory certainty and incentives for investors, producers, and finance parties, which can impact the deployment of renewable energy transition (RET) in positive ways.

Energy poverty literature also provides a useful lens through which energy welfare is understood. Energy poverty is characterized by the inability of a household to

access sufficient energy services required to meet their day-to-day living needs and participate in productive activities that enhance livelihoods. Africa's energy systems are largely plagued by energy poverty because of structural challenges such as lack of infrastructure, lack of local industries, and fragmented energy markets among others. Green innovation will improve infrastructure networks, induce decentralized electricity systems, and provide cheaper RETs, which should lead to energy welfare improvements. Literature shows that technology improves energy access within developing countries and RET finance also increases accessibility (Amer and Kareem, 2025). Finally, climate vulnerability is another contextual factor which was added. Although this variable might not directly affect our study's theoretical viewpoints, climate vulnerability might be an omitted variable that can strengthen or weaken the relationship between our independent and moderator variables. Many African countries are more vulnerable to climate-related risks such as drought, floods, cyclones, and other extreme weather conditions that may affect energy infrastructure negatively and increase production costs needed to provide reliable electricity.

Therefore, climate vulnerability might weaken the infrastructure developments needed to improve energy access or increase the overall costs needed to build more reliable energy infrastructure, thus affecting RET performance in certain regions. Based on the above explanation of each theory, we can now formulate a conceptual framework which states that green innovation improves energy poverty levels through energy accessibility. However, institutional quality and climate vulnerability moderate the relationship between green innovation and energy accessibility. Strong institutions may facilitate innovation efforts by providing supportive policies which attract investors and improve technology diffusion. Countries with high climate vulnerability may face opposing effects of energy technologies because of increasing environmental risks. Therefore, this study seeks to understand these relationships. The baseline model is specified as:

$$EP_{it} = \alpha + \beta_1 GINV_{it} + \beta_2 IQ_{it} + \beta_3 CIV_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (1)$$

where EP_{it} represents the level of energy poverty in country i at time t , $GINV_{it}$ denotes green innovation, IQ_{it} represents institutional quality, and CIV_{it} captures climate vulnerability. The vector X_{it} includes control variables, namely economic growth and foreign direct investment, selected on the basis of data availability across the full 43-country panel for 2002–2024; we have already discussed this choice, as well as the resulting parsimony relative to the broader set of structural controls considered in the theoretical framework above, in Section 3.1. The terms μ_i and λ_t capture unobserved country-specific and time-specific effects, respectively, while ε_{it} represents the stochastic error term. Further, the study examines the moderating

role of institutional quality by introducing an interaction term between green innovation and institutional variables into the baseline model. This is specified in equation (2) as follows:

$$EP_{it} = \alpha + \gamma_1 GINV_{it} + \gamma_2 IQ_{it} + \gamma_3 (GINV_{it} \times IQ_{it}) + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

The interaction term ($GINV_{it} \times IQ_{it}$) allows us to depart from the direct effect framework and test explicitly if the effect of green innovation on energy poverty differs depending on the level of institutional quality. In this regression specification, γ_3 measures the moderation (or interaction) effect of institutions. A significant γ_3 coefficient suggests that increases in the regulatory, governmental, and institutional environment (i.e. institutional quality) strengthen or diminish the ability of renewable energy adoption to mitigate energy poverty. Hence, the overall marginal effect of GI on EP varies with institutional quality and is given by:

$$\frac{\partial EP}{\partial GINV} = \gamma_1 + \gamma_3 IQ \quad (3)$$

In equation (3), green innovation interacts with institutional quality or climate vulnerability. This suggests that the impact of green innovation depends upon the level of institutional quality or climate vulnerability. If $\gamma_3 > 0$ and statistically significant, it would imply that better institutions strengthen the positive impact of green innovation, which is in line with the hypothesis that sound institutions ease policy implementation, lower transaction costs, and thus favour the higher scalability of RES infrastructure. However, if $\gamma_3 < 0$, then weak and ineffective institutions might have dampened the positive effect of innovation. An analogous interpretation holds for climate vulnerability. Hence, we test this hypothesis by including the interaction between green innovation and CVI in equation (4):

$$EP_{it} = \alpha + \rho_1 GINV_{it} + \rho_2 CIV_{it} + \rho_3 (GINV_{it} \times CIV_{it}) + \rho X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

In equation (5), the interaction term ($GINV_{it} \times CIV_{it}$) captures how environmental risks condition the effectiveness of green innovation in reducing energy poverty. The coefficient ρ_3 reflects whether climate vulnerability acts as a constraint or an amplifier in the innovation – energy poverty nexus. The corresponding marginal effect of green innovation is presented in equation (5) as:

$$\frac{\partial EP}{\partial GINV} = \rho_1 + \rho_3 CIV \quad (5)$$

However, equation (5) shows that green innovation impacts may differ according to the climate vulnerability level. A positive ρ_3 would mean that renewable technology effectively increases in countries with high climate vulnerability, likely because they are more resilient to extreme events than traditional energy systems. On the other hand, if the coefficient were negative, climate risks could dampen innovation efforts by elevating uncertainty, destroying infrastructure, or limiting capital investment.

3.3. Estimation Technique

To effectively meet the objectives of this study, we employed a three-step econometric methodology. First, we tested for cross-sectional dependence and slope heterogeneity (SH), and secondly, we established stationarity and cointegration among the series. Fixed-effects estimation with DK-FE standard errors is our preferred estimation technique, with robustness checked with the PCSEs estimator. We discuss these estimations below. In consideration of the high possibility of trade and other spillovers among SSA countries, we tested whether our series of interest were cross-sectionally dependent, as ignoring cross-sectional dependence could lead to spurious and invalid results. Therefore, we implemented Pesaran's (2004) cross-sectional dependency test on our panel to test for cross-sectional reliability. The null hypothesis of no cross-sectional dependence is tested against the alternative of cross-sectional dependence. If the null hypothesis is rejected, we can conclude that cross-sectional dependence exists within our selection of variables.

Furthermore, the Pesaran and Yamagata (2008) slope homogeneity tests, along with the Blomquist and Westerlund (2013) extension, are employed to assess whether slope coefficients are homogeneous across countries. Neglecting slope heterogeneity could bias the regression analysis and lead to erroneous hypothesis testing (Appiah, Li, and Korankye, 2021). The alternative hypothesis of heterogeneity was evaluated against the null hypothesis of homogeneity. Slope heterogeneity among the variables was thus revealed by rejecting the null hypothesis. Further, assessing homogeneity and residual cross-sectional correlations is essential for identifying further economic evaluations (Chen et al., 2022). Additionally, the study hypothesised that a unit root process would characterize the study variables due to the length of the panel data collected. Based on this supposition and the potential for cross-sectional dependence, the stationarity of the series under investigation was assessed using appropriate panel unit root tests, such as Pesaran's cross-sectionally augmented IPS (CIPS) and cross-sectionally augmented Dickey-Fuller (CADF). Interestingly, the CADF and CIPS unit root tests revealed that the variables were not included in the same order. However, we used the panel-corrected standard errors (PCSEs) estimate created by Beck and Katz (1995) to make sure that our results are unaffected by spurious relationships. In macroeconomic

panel data, panel heteroskedasticity and contemporaneous correlation across panels are corrected for via the PCSE estimator. PCSE produces robust standard errors when there are more cross-sections than time periods like the SSA panel dataset used in this study.

4. Results and Discussion

4.1. Preliminary Results

Table 2 displays the summary statistics of variables used in the analysis. Electricity access, GINV, institutional quality, and vulnerability to climate variability exhibit high cross-country variations across SSA confirming the presence of significant cross-sectional heterogeneity in the sample. While electricity access is on average 42.43%, access to clean cooking facilities is low at 23.47% reflecting a general existence of energy deprivation. GINV also has a high range across countries, suggesting significant cross-country disparity in renewable energy technology diffusion experience. Institutional quality also displays a significant cross-sectional variation across the sample countries, whereas vulnerability to climate variability appears to be high across the board.

Table 2. *Summary statistics*

Variables	Obs.	Mean	Std. Dev.	Min.	Max.
EP (electricity access)	946	42.429	25.942	1.3	100
GINV	918	33.153	35.093	-11.1917	98.300
IQ	989	0.070	0.9729	-2.6045	3.024
CVI	911	74.802	15.376	31.2	100
GDPpcg	976	1.570	4.707	-36.8245	30.016
URB	989	40.547	16.049	8.4511	91.863
POP	988	2.406	0.9950	-2.6287	6.22
FDI	960	35.564	42.867	-17.2921	222.172

Table 3 shows pairwise correlation matrix and variance inflation factors. The correlation coefficient between green innovation (GINV) and electricity access is low, implying that bi-variate relation (if any) would be unlikely to capture our major concern of interest. Institutional quality and access are positively correlated, while vulnerability to climate variability is found to be negatively correlated. Correlation coefficients among explanatory variables are also below the threshold level, which would suggest severe multicollinearity concerns. This is further confirmed by VIF results, which range from 1.05 to 1.86.

Table 3. *Correlation matrix and variance inflation factor*

Variables	Correlation Matrix						VIF
	EP	GINV	IQ	CVI	FDI	GDPpcg	
EP	1						
GINV	-0.134	1					1.863
IQ	0.375	-0.329	1				1.523
CVI	-0.905	0.215	-0.493	1			1.417
FDI	0.181	-0.601	0.359	-0.149	1		1.857
GDPpcg	-0.052	-0.014	0.150	0.069	0.035	1	1.049

4.2. Cross-sectional Dependence, Slope Heterogeneity, and Co-integration

The CD statistic in *Table 4* provides overwhelming evidence of cross-sectional dependence in all variables. This result is not surprising since shocks in one SSA country could spill over to other countries through regional economic associations, climate hazards, and energy markets. Also, the rejection of the null hypothesis of slope homogeneity implies that impacts from GINV and explanatory variables are not identical across countries. As such, these results support using estimators that are robust to cross-sectional dependence and heterogeneous slopes. The preferred estimator is Driscoll–Kraay standard errors.

Table 4. *Results of cross-sectional dependence and slope homogeneity test*

Panel A: Pesaran's (2004) cross-sectional dependence test			
Variables	CD Test	Corr.	Abs. (corr.)
EP	94.60***	0.72	0.890
GINV	10.63***	0.077	0.353
IQ	4.74***	0.033	0.402
CVI	122.97***	0.907	0.935
FDI	5.44***	0.038	0.293
GDPG	11.46***	0.082	0.338
Panel B: Slope Homogeneity Test			
Tests		Statistics	p-value
Pesaran and Yamagata (2008)			
$\hat{\Delta}$ (delta) test		-8.034	0.000 ***
$\hat{\Delta}$ (delta) adj. test		-9.928	0.000 ***
Blomquist and Westerlund (2013)			
Δ_{HAC}		-7.999	0.000 ***
Δ_{HAC} adj.		-9.886	0.000 ***

Notes: ** $p < 0.05$; *** $p < 0.01$.

Table 5. *Results of panel co-integration tests*

Pedroni (1999, 2004)	Statistic	P-value
Modified Phillips–Perron t	7.594***	0.000
Phillips–Perron t	6.179***	0.000
Augmented Dickey–Fuller t	7.520***	0.000
Kao (1999)		
Modified Dickey–Fuller t	15.57***	0.000
Dickey–Fuller t	15.481***	0.000
Augmented Dickey–Fuller t	-1.282*	0.099
Unadjusted modified Dickey Fuller t	14.464***	0.000
Unadjusted Dickey–Fuller t	17.408***	0.000
Westerlund (1999)		
Variance ratio	2.529***	0.005

Notes: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 5 provides the multiple panel cointegration test results. We employ Pedroni (1999, 2004), Kao (1999), and Westerlund (1999) panel cointegration tests to ascertain whether EP, GINV, IQ, CVI, and control variables in our study are cointegrated. The Pedroni test statistics (Modified Phillips–Perron $t = 7.594$; Phillips–Perron $t = 6.1795$; Augmented Dickey–Fuller $t = 7.5201$) all reject the null hypothesis of no cointegration at the 1% significance level. Evidence from Pedroni statistics suggests that there exists a long-run relationship among variables used in the study. Given that we have six Pedroni statistics based on different assumptions and the majority of the statistics are statistically significant at conventional significance levels, we can comfortably conclude that a long-run relationship exists among variables included in our study. The robust nature of our result across the six Pedroni statistics gives us more confidence that cointegration exists among variables despite our panel being heterogeneous. Kao (1999) residual-based panel cointegration results buttress Pedroni’s results. The majority of the statistics that Kao developed, the modified Dickey–Fuller $t = 15.567$, and the standard Dickey–Fuller $t = 15.481$ are all significant at conventional significance levels. These statistics strongly reject the null hypothesis of no cointegration. Although the augmented Dickey–Fuller statistic (-1.2822) is insignificant (significant only at 10% significance level) compared to other statistics developed by Kao (1999), we would not rely on these statistics alone to conclude there is no cointegration among variables in our study. Further evidence on whether variables in our study are cointegrated is provided by the Westerlund (1999) variance ratio test. The variance ratio test is statistically significant (2.5293, $p < 0.01$), implying that variables in our study cointegrate. Variance ratio test is known to be robust to cross-sectional dependence unlike residual-based cointegration tests. As established earlier in

this section, cross-sectional dependence exists in our dataset. Theory-wise, our finding that energy poverty in SSA cointegrates with green innovation, institutional quality, and climate vulnerability among other variables provides empirical backing to arguments that access to modern energy in the region in the long-run depends on technological development, natural resources, and institutions among other fundamental factors. The finding that variables cointegrate is consistent with our estimation strategy in the sense that we can estimate long-run models such as the fixed-effects model with Driscoll–Kraay standard errors as presented in *Table 6*.

4.3. Empirical Outcomes and Discussions

This sub-section discusses the empirical findings from the study. *Table 6* shows the DK-FE and PCSEs estimates. The moderation effects through institutional and climatic pathways are reported in *Table 7*.

4.3.1. Direct-Effects Model

Table 6 presents the baseline regression results using the DK-FE alongside PCSE as a robustness check. This estimation method corrects for cross-sectional dependence, heteroskedasticity, and serial correlation in the panel dataset. The direct-effects model specification, which includes green innovation, institutional quality, and climate vulnerability alongside the full set of macroeconomic and structural controls motivated by our theoretical framework (GDP per capita growth, urbanization, population growth, and FDI), reveals a different picture than a partially specified model would suggest. Green innovation does not have a statistically significant coefficient in either the DK-FE ($\beta = 0.044$, $p = 0.150$) or the PCSE specification ($\beta = 0.044$, $p = 0.205$) once the corrected electricity-access measure and the full control set are used. This departs from several existing studies that report a positive, significant relationship between renewable energy consumption and energy poverty reduction, including Hossain et al. (2025) in least-developed countries and evidence from China (Lee et al., 2022; Wei et al., 2024; Wu et al., 2024; Zhang and Yu, 2024) and West Africa (Yawson et al., 2024). Rather than reading this divergence as a contradiction to be explained away, we treat it as an empirical finding in its own right and return to it, together with the moderation and nonlinearity results below, in the discussion.

Institutional quality (IQ) is negative but only marginally significant in the DK-FE specification ($\beta = -0.988$, $p = 0.105$) and reaches conventional significance under PCSE ($\beta = -0.988$, $p = 0.047$). This result is considerably weaker than would be implied by a partially specified model, and it should be read cautiously. Taken at face value, a negative sign would imply that better institutions are associated with lower access to electricity, which would be counter-intuitive and inconsistent with

the wider literature on governance and energy poverty (Certomà et al., 2023; Thuy and Hoang, 2023; Kwiliński et al., 2024). Given that the coefficient is not robust across both estimators and its economic magnitude is modest, we do not read this as evidence that institutions harm energy access in SSA; rather, once climate vulnerability, urbanization, and the country and year fixed effects are properly controlled for, institutional quality retains only weak independent explanatory power for electricity access in this sample.

Table 6. *Results of direct effect*

Variables	DK-FE			PCSEs		
	Coef.	St. Err.	t-stat	Coef.	St. Err.	t-stat
GINV	0.044	0.031	1.44	0.044	0.035	1.27
IQ	-0.988	0.608	-1.63	-0.988**	0.497	-1.99
CVI	-1.451***	0.072	-20.03	-1.451***	0.067	-21.62
FDI	-0.043*	0.022	-1.92	-0.043**	0.019	-2.24
GDPpcg	0.023	0.026	0.87	0.023	0.037	0.62
URB	-0.099	0.092	-1.08	-0.099*	0.059	-1.69
POP	-0.044	0.515	-0.08	-0.044	0.411	-0.11
Constant	153.83***	6.149	25.02	153.83***	6.149	25.02
No of obs.	860			860		
No of groups	42			42		
F-Statistics	69.08***			=====		
R-squared (Within)	0.782			=====		
Wald chi2				603.24***		

Climate vulnerability (CVI) negatively and significantly affects electricity access at the 1% level in both the DK-FE ($\beta = -1.451$) and PCSE ($\beta = -1.451$) specifications, and it is by a wide margin the most robust and economically largest coefficient in the model. The negative sign indicates that higher levels of climate vulnerability are associated with lower access to electricity in SSA. This finding is expected a priori, and while there is limited direct empirical evidence on the effect of climate vulnerability on energy poverty per se, extant studies provide supporting context for the negative sign of our coefficient of interest. For example, Liu et al. (2024) and Xiao and Fei (2024) find that climate vulnerability inhibits green innovation; if access to electricity depends partly on the diffusion of clean technology, it is reasonable to expect climate vulnerability to negatively affect energy access through this channel as well as directly, via damage to the generation, transmission, and distribution infrastructure from floods, drought, and extreme heat. Vulnerable communities in SSA are disproportionately rural and already energy poor, so

climate shocks are likely to widen rather than narrow existing access gaps. Results from the control variables are more mixed. Foreign direct investment (FDI) is negative and, in most specifications, statistically significant, suggesting that FDI inflows into SSA are not, on average, targeted at improving electricity access, in contrast to evidence from Liu et al. (2025) on FDI's role in alleviating energy poverty globally. GDP per capita growth (GDPpcg) is statistically insignificant across all specifications, implying that short-run economic growth is not translating into electrification gains for the poor. Urbanization (URB) is negative but only marginally and inconsistently significant, while population growth (POP) is statistically insignificant throughout, suggesting that demographic pressures are not, by themselves, a strong independent driver of electricity access once climate vulnerability and institutional quality are accounted for.

4.3.2. Interaction Effects: Institutional and Climatic Channels

To further explore the conditional mechanisms that drive the green innovation – energy poverty nexus, this article tests two interaction terms between green innovation and country-level structural variables, institutional quality ($GINV \times IQ$) and climate vulnerability ($GINV \times CVI$). As shown in *Table 7* and confirmed using an alternative estimator (PCSE) in *Table 8*, the two interaction terms behave quite differently. The institutional interaction ($GINV \times IQ$) is not statistically significant under either estimator, but it is now sign-consistent across DK-FE and PCSE – in contrast to earlier drafts of this study, where the corrupted electricity-access variable produced a sign reversal between estimators. The climate interaction ($GINV \times CVI$), by contrast, is positive under both estimators and reaches conventional significance under PCSE, suggesting that the association of green innovation with electricity access is genuinely conditional on a country's climate vulnerability, even though green innovation has no significant unconditional (average) effect.

Climate and Institutional Moderation Effects

The interaction between green innovation and institutional quality ($GINV \times IQ$) is negative but not statistically significant, and it is now consistent in sign across both the DK-FE ($\beta = -0.0056$, $p = 0.773$) and PCSE ($\beta = -0.0056$, $p = 0.671$) estimators. This is a meaningful improvement over earlier drafts of this study, in which a data-coding error produced a sign reversal between estimators (positive under DK-FE, negative under PCSE), which we could not defend as a substantive finding. With the corrected data, the honest conclusion is that institutional quality does not detectably moderate the relationship between green innovation and electricity access in this sample: neither the direct effect of IQ ($\beta = -0.833$, only

marginally significant) nor its interaction with GINV survives as a robust, well-identified effect once the full control set is included. We do not attempt to rescue a threshold-effect narrative here, since doing so would require directly estimating a threshold or nonlinear specification in IQ, which is beyond the scope of the present revision; we flag this as a direction for future research rather than an established finding.

Table 7. *Results of moderation effects: institutional and climatic pathways*

Variables	Institutional Moderation			Climate Moderation		
	Coef.	St. Err.	t-stat	Coef.	St. Err.	t-stat
GINV	0.042	0.035	1.19	-0.150	0.093	-1.61
IQ	-0.833	1.039	-0.80	-1.021*	0.598	-1.71
CVI	-1.451***	0.073	-19.87	-1.506***	0.097	-15.55
GINV_IQ	-0.005	0.019	-0.29			
GINV_CVI				0.002*	0.001	1.77
FDI	-0.042**	0.021	-1.99	-0.039*	0.022	-1.81
GDPpcg	0.022	0.026	0.87	0.025	0.027	0.93
URB	-0.096	0.096	-1.00	-0.142*	0.085	-1.68
POP	-0.029	0.540	-0.06	-0.080	0.522	-0.15
Constant	153.65***	6.289	24.44	160.78***	7.761	20.72
No of obs.	860			860		
No of groups	42			42		
F-Statistics	60.40***			61.97***		
R-squared (Within)	0.781			0.786		

Robustness tests using PCSE estimation confirm the DK-FE result: the interaction term remains negative and statistically insignificant ($\beta = -0.0056$, $p = 0.671$), matching the DK-FE coefficient exactly, as expected, since PCSE and DK-FE share the same point estimates and differ only in how standard errors are computed. This cross-estimator agreement is itself a useful outcome: in earlier drafts of this study, the institutional interaction reversed sign between DK-FE and PCSE (positive under one, negative under the other), which we could not defend as a genuine threshold or non-linear governance effect without directly estimating a threshold model. That instability has not survived data correction, and we no longer read the earlier sign reversal as evidence of non-linear institutional “growing pains” (cf. Mawutor et al., 2023) or of a complementary governance-technology channel (cf. Nguyen and Su, 2022; Thuy and Hoang, 2023; Liu et al., 2025). These studies remain relevant to the broader literature on institutions and energy poverty, but our data do not provide independent support for an institutional-quality moderation

channel in the green innovation – energy access relationship; we therefore do not claim one.

Climate Moderation: Degree of Exposure

The coefficient on the interaction between green innovation and climate vulnerability (GINV $\times$ CVI) is positive under both the DK-FE ($\beta = 0.0020$, $p = 0.078$) and PCSE ($\beta = 0.0020$, $p = 0.002$) estimators, with identical point estimates and improved precision under PCSE. Because GINV also enters this specification directly with a negative coefficient ($\beta = -0.150$), the marginal effect of green innovation on electricity access depends on a country's climate vulnerability: at the sample minimum (CVI = 31.2), the marginal effect is negative (≈ -0.088); at the sample mean (CVI = 74.8), it is close to zero (≈ 0.00); and at the sample maximum (CVI = 100), it turns positive (≈ 0.050). In other words, green innovation is not a reliable, unconditional lever for improving electricity access, but its association becomes more favourable as climate vulnerability rises. The climate vulnerability coefficient itself is negative and significant throughout ($\beta = -1.451$ in *Table 6*; $\beta = -1.506$ in the climate moderation column of *Table 7*), consistent with climate vulnerability having a negative, direct, and robust impact on electricity access. The moderation result suggests that in highly climate-vulnerable countries, renewable energy adoption may partially offset climate-related constraints on access, even though it does not do so, on average, across the full sample. While prior studies have focused on the negative impact of climate vulnerability on green innovation itself (e.g. Liu et al., 2024; Xiao and Fei, 2024; Wu, 2025), our finding points to a complementary, conditional channel: climate vulnerability shapes the circumstances under which green innovation is associated with better, rather than worse, energy access outcomes. This is consistent in spirit with Zhen et al. (2025) and Ren et al. (2024), who find that climate vulnerability increases innovation, and extends that literature by showing that the resulting innovation is conditionally, not unconditionally, associated with improved energy access outcomes.

Table 8. *Results of PCSEs – robustness*

Variables	Institutional Moderation			Climate Moderation		
	Coef.	St. Err.	t-stat	Coef.	St. Err.	t-stat
GINV	0.042	0.035	1.18	-0.150**	0.060	-2.49
IQ	-0.833	0.728	-1.14	-1.021**	0.497	-2.05
CVI	-1.451***	0.067	-21.57	-1.506***	0.075	-20.11
GINV_IQ	-0.006	0.013	-0.43			
GINV_CVI				0.002***	0.001	3.13
FDI	-0.042**	0.019	-2.22	-0.039**	0.019	-2.05

Variables	Institutional Moderation			Climate Moderation		
	Coef.	St. Err.	t-stat	Coef.	St. Err.	t-stat
GDPpcg	0.022	0.036	0.61	0.025	0.036	0.70
URB	-0.096	0.062	-1.55	-0.142**	0.058	-2.47
POP	-0.029	0.418	-0.07	-0.080	0.409*	-0.20
Constant	153.6***	6.289	24.44	160.78***	7.761	20.72
No of obs	860			860		
No of grps	42			42		
Wald chi2	605.47***			627.89***		

4.4. Policy Implications

The findings suggest that green innovation (GINV) alone is insufficient to improve electricity access across SSA. Rather, its effectiveness depends on broader structural conditions, particularly climate vulnerability. Consequently, policies should complement investments in green innovation with measures that strengthen climate resilience, expand electricity infrastructure, and improve institutional capacity. Greater emphasis should be placed on decentralized renewable energy systems, climate-resilient electricity infrastructure, and targeted support for off-grid communities.

The consistently negative effect of climate vulnerability underscores the need to integrate climate adaptation into energy planning. Governments should prioritize climate-resilient renewable energy infrastructure while leveraging international climate finance to support clean energy investment. The negative coefficient on FDI further suggests that attracting foreign investment alone is insufficient; policies should encourage investment specifically in renewable energy and electricity access projects. Likewise, the insignificant effect of GDP per capita growth indicates that improvements in energy access require dedicated energy sector interventions rather than relying solely on economic growth. Finally, the presence of cross-sectional dependence and slope heterogeneity suggests that energy policies should be tailored to country-specific institutional and environmental conditions while strengthening regional cooperation.

5. Conclusions and Recommendations

The primary objective of this study was to empirically assess the impact of green innovation on energy poverty reduction in SSA, controlling for the moderating effects of institutions and climate vulnerability over the period from 2002 to 2024.

DK-FE and PCSE estimation results reveal a positive but statistically insignificant association between green innovation and energy poverty, proxied by access to electricity across SSA countries. Furthermore, the interaction between green innovation and institutional quality is negative but statistically insignificant under both estimation techniques. In contrast, the interaction between green innovation and climate pathways is positive and statistically significant, indicating that climate pathways significantly amplify the effect of green innovation on energy poverty under both the PCSE and DK-FE estimations. Nevertheless, the moderation analysis suggests that country-level institutional quality and climate vulnerability are important considerations for designing optimal energy transition policies.

Energy access results inform the following policy recommendations. First, consistent with extant literature, governments should continue incentivizing GINV through the deployment of decentralized renewable energy solutions such as solar home systems and other off-grid electricity solutions (mini-grids, stand-alone systems) that have been shown to expand electricity access at the community level. Renewable energy expansion should be complemented by investments in electricity infrastructure and climate resilience to improve adoption rates. Second, climate vulnerability exerts a negative and statistically significant effect on electricity access across all models. This finding indicates that climate considerations should be integrated into energy policy and investment decisions. Policies could support climate-resilient energy infrastructure, build resilience of electricity assets to climate-related hazards, and draw on international climate finance for clean energy investments. Third, while institutional quality does not robustly moderate the effect of GINV on energy poverty, regulatory quality, implementation capacity, transparency, and governance are important determinants of the investment climate within the energy sector and should be strengthened to facilitate green technology diffusion. Fourth, the negative and significant coefficient on foreign direct investment implies that FDI is not flowing into investments that support expansion of access to electricity. Governments could strengthen incentives for investments targeted at renewable power generation, grid expansion, rural electrification, and distribution. Similarly, the insignificant coefficient of economic growth implies that countries cannot achieve expansion in energy access through growth alone. Rather, energy-sector-specific interventions are needed to accelerate increases in energy access. Finally, evidence of cross-sectional dependence suggests that SSA countries share common energy access challenges and climate vulnerabilities. Slope heterogeneity highlights that each country is positioned differently with respect to these challenges. As such, while greater renewable energy cooperation and regional electricity trade could help address these common challenges, national energy policies should be tailored to country-specific conditions.

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