International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2026, 16(1), 577-586.

Exploring the Role of Renewable Energy Technologies in Mitigating Energy Poverty in Sub-Saharan Africa

Darlington Chizema[1]*, Ramos E. Mabugu[2], Christelle Meniago[1]

[1]Faculty of Economic and Management Sciences, Sol Plaatje University, Kimberley, South Africa, [2]Department of Accounting and Economics, Faculty of Economic and Management Sciences, Sol Plaatje University, South Africa. *Email: darlington.chizema@spu.ac.za

Received: 18 June 2025 **Accepted:** 21 October 2025 **DOI:** https://doi.org/10.32479/ijeep.21369

ABSTRACT

This study examines the effect of renewable energy consumption on energy poverty across 43 Sub-Saharan African countries from 2002 to 2021. Using a dynamic panel data approach and a two-step System GMM estimator, it addresses endogeneity concerns in energy poverty analysis. Results show energy poverty is persistent, reflecting deep institutional and infrastructural challenges. While renewable energy consumption is positively associated with energy poverty, the modest impact suggests current investments are concentrated in urban or grid-connected areas, with limited benefits for rural populations. This highlights the need for inclusive, decentralized energy strategies. Human capital emerges as a key factor in alleviating energy poverty, emphasizing the importance of integrating energy access with education and health initiatives. Conversely, GDP per capita, institutional quality, and population density show no significant effects, challenging assumptions that economic growth alone can resolve energy deprivation. The lack of a declining trend in energy poverty underscores the urgency for targeted, long-term interventions. The study advocates pro-poor energy policies, innovative financing, and multi-sectoral approaches linking energy access to broader development goals to advance Sustainable Development Goal 7 (SDG 7). Future research should explore subnational disparities and the varied impacts of renewable technologies to inform context-specific solutions.

Keywords: Renewable Energy, Energy Poverty, Sub-Saharan Africa, Dynamic Panel Data, System GMM, Sustainable Development Goal 7
JEL Classifications: Q420, Q010, O13

1. INTRODUCTION

According to Singh and Inglesi-Lotz (2021), energy poverty is defined as the lack of access to modern, reliable and affordable energy services and remains one of the most pressing developmental challenges in Sub-Saharan Africa (SSA). The region continues to exhibit the highest concentration of energy-deprived populations globally, with over 580 million people lacking access to electricity and more than 900 million relying on traditional biomass for cooking (Michoud and Hafner, 2021; Nforngwa, 2023). In 2012, approximately 625 million people in the SSA had no electricity, which is approximately 80% of the global population lacking access to modern energy services (Singh and Inglesi-Lotz, 2021; Nforngwa, 2023). This chronic energy deficit imposes significant constraints on economic growth, human capital development, and overall welfare. The World Economic Forum, as cited by Nforngwa (2023), estimates that inadequate power infrastructure results in a loss of 2-4% of SSA's gross domestic product (GDP) annually, underscoring the macroeconomic implications of energy poverty.

The adverse effects of energy poverty extend beyond household consumption and impact firm productivity, public service delivery, and environmental sustainability. For example, the widespread reliance on traditional biomass, such as firewood and charcoal, contributes to deforestation, indoor air pollution, and adverse health outcomes, particularly among women and children (Leal Filho et al., 2024; Nforngwa, 2023). Moreover, Cai (2024) notes that only about 28% of the population in SSA has access to a reliable electricity supply, with frequent outages and load shedding undermining industrial competitiveness and investment. As the region's population is projected to double by 2050, the demand for energy will increase substantially, intensifying the urgency of achieving universal access (Cai, 2024).

The persistence of energy poverty in SSA is attributable to a confluence of structural factors, including inadequate infrastructure, limited fiscal capacity, and institutional weaknesses. Traditional grid-based electrification has proven insufficient in addressing the dispersed and low-income populations that characterize much of the region (Wang et al., 2023). In this context, renewable energy technologies (RETs), such as solar photovoltaics, wind turbines, mini-hydropower, and biogas systems, offer a decentralized and scalable alternative. RETs are increasingly recognized for their potential to expand energy access, reduce greenhouse gas emissions, and stimulate local economic development (Ambole et al., 2021; IRENA, 2023). Their declining costs and technological maturity make them particularly suitable for off-grid and mini-grid applications in rural and peri-urban areas.

SSA remains the epicentre of global energy poverty, with more than 85% of the world's population lacking electricity residing in the region as of 2023, up from 50% in 2010 (IEA, IRENA, UNSD, World Bank and WHO, 2025). This persistent deficit in energy access presents a major constraint to economic development, human capital formation, and poverty alleviation. Addressing energy poverty is crucial for reducing broader poverty and inequality, as energy access enables economic opportunities, education, and healthcare improvements. Within the framework of the United Nations Sustainable Development Goals (UNSD) SDGs goal 7 (SDG 7) aims to "ensure access to affordable, reliable, sustainable and modern energy for all" by 2030. Achieving this goal is foundational not only for improving household welfare but also for enabling progress in health, education, and inclusive economic growth. Decentralized RETs such as solar home systems and mini grids have emerged as economically viable alternatives to traditional grid expansion, particularly in rural and underserved areas where grid extension is financially and logistically prohibitive. Between 2020 and 2022, these technologies accounted for 55% of new electricity connections in SSA, highlighting their transformative potential in bridging the energy access gap (IEA, IRENA, UNSD, World Bank and WHO, 2025). RETs offer scalable solutions that align with market-based approaches and public-private partnerships, making them strategic tools for sustainable development.

Despite global advancements in renewable energy technologies and increasing commitments to sustainable development, energy poverty remains a persistent and deeply entrenched challenge in Sub-Saharan Africa (Gina and Mutambara, 2024. SSA remains significantly off-track in achieving universal energy access. If current trends persist, nearly 600 million people in the region may still lack electricity by 2030 (Mukhtar et al., 20223; Leal Filho et al., 2024). While renewable energy is widely promoted as a solution to energy poverty due to its scalability, sustainability, and off-grid potential, empirical evidence on its actual impact remains mixed and context-dependent. Many renewable energy initiatives have failed to reach the most energy deprived populations or have been implemented without sufficient integration into broader development strategies. As a result, the effectiveness of renewable energy in reducing energy poverty in Sub-Saharan Africa remains uncertain and underexplored in academic literature. RETs should be viewed not merely as technological interventions, but as strategic instruments for inclusive growth and structural transformation. As Ambole et al. (2021) emphasized, the deployment of RETs must be embedded within holistic frameworks that promote institutional reform, human development, and socio-economic empowerment.

Much of the existing literature has focused on the role of energy access in promoting broader development outcomes such as economic growth, human wellbeing, and poverty reduction (Brown et al., 2025; Khobai, 2021; Simionescu et al., 2024; Singh and Inglesi-Lotz, 2021; Soto and Martinez-Cobas, 2025). While these studies underscore the developmental importance of energy, they often overlook the direct and sustained impact of renewable energy technologies (RETs) on reducing energy poverty itself. As a result, the specific contribution of RETs to improving energy access among marginalized populations remains underexplored and empirically underdeveloped. Moreover, some studies that do examine the relationship between RETs and energy poverty frequently suffer from methodological limitations. These include inadequate treatment of endogeneity, failure to account for unobserved heterogeneity, and neglect of the dynamic nature of energy poverty, often due to a predominant reliance on descriptive analyses, surveys, or bibliometric approaches (Gina and Mutambara, 2024; Leal Filho et al., 2024). A further limitation lies in how energy poverty is measured. Many studies rely on broad proxies such as national electrification rates or per capita energy consumption, which may obscure localised and persistent forms of deprivation. To address this, the present study adopts a more targeted approach by calculating energy poverty as the lack of access to electricity, derived from the Access to Electricity Index. This custom metric enables a more precise quantification of energy poverty at the country level, capturing both the extent and persistence of electricity deprivation. By focusing on actual access rather than aggregate consumption, the study enhances the relevance of its findings for policy design and evaluation.

This study responds to these conceptual and methodological gaps by employing a two-step System GMM estimator, which is particularly well-suited for dynamic panel data analysis. This method allows for the inclusion of lagged dependent variables to account for persistence in energy poverty and the control of unobserved country-specific heterogeneity. Furthermore, the study introduces a custom measurement of energy poverty, calculated as the lack of access to electricity using data from the Access to Electricity Index. This approach provides a more precise and policy-relevant assessment of energy deprivation than conventional proxies. By integrating a robust methodological framework with a refined measurement of energy poverty, the study contributes novel empirical insights to the discourse on sustainable energy transitions in SSA. It offers evidence-based guidance for policy interventions aligned SDG 7 while advancing the academic literature on the effectiveness of RETs in addressing persistent energy poverty.

2. REVIEW OF THE LITERATURE

2.1. Energy Poverty

Energy plays a pivotal role in fostering macroeconomic development, environmental sustainability, poverty alleviation, employment generation, gender equity, and improvements in education and health outcomes, thus contributing significantly to broader human development objectives (UNDP, 2005).). Within the economic development discourse, energy is recognized not only as a commodity but as a foundational input to production, human capital formation, and the enhancement of social welfare. However, the concept of energy poverty remains complex and context-dependent, lacking a universally accepted definition (Bednar and Reames, 2020). The literature presents a range of interpretations reflecting diverse socio-economic and geographic realities (Day et al., 2016; González-Eguino, 2015). According to the International Energy Agency (IEA), energy poverty encompasses the absence of access to electricity, clean fuels, and adequate energy infrastructure, coupled with a dependence on traditional biomass and inefficient energy sources (Barnes et al., 2011).).

The definition of energy poverty varies significantly between developing and developed economies. In developing countries, it is mainly characterized by the lack of access to modern energy services, which limits economic productivity and human development. In contrast, in developed economies, energy poverty is often defined in terms of affordability, where high energy costs, low household incomes, and inefficient housing stock lead to inadequate energy consumption, thereby affecting living standards (Sadath and Acharya, 2017). Scholars have further expanded the definition to include broader social and economic dimensions. Bouzarovski and Petrova (2015) describe energy poverty as encompassing infrastructure deficits, economic inequality, and social exclusion. Others define it as the inability to pay for essential energy services, such as heating, cooling, lighting, mobility, and power, necessary for a minimum standard of living (Koukoufikis et al., 2023; Jones, 2016). Zhao et al. (2022) emphasize the lack of access to clean fuels and associated services, while Bouzarovski (2014) frames it as the deprivation of socially and materially necessary energy services within the home.

Energy poverty is increasingly recognized as a complex and multidimensional phenomenon that includes economic, infrastructural, and social dimensions. As Zhao et al. (2022) note, this complexity has led scholars to adopt more comprehensive analytical frameworks to assess its scope and implications. One of the most widely used tools in this regard is the Multidimensional Energy Poverty Index (MEPI), which evaluates deprivation in access to modern energy services across several dimensions (Nussbaumer et al., 2012). Building on this approach, Okushima (2017) proposes a framework tailored to developed economies, incorporating three key components: energy income, energy cost, and energy efficiency. Given the multifaceted nature of energy poverty, no single indicator can fully capture its extent. As Szpak and Ostrowski (2025) argue, a range of indicators are necessary to assess both its intensity and prevalence. These include measures such as utility bill arrears, low absolute energy expenditure, a high share of energy costs relative to income, and the inability to maintain adequate indoor temperatures (Siksnelyte-Butkiene et al., 2021; Calama-González et al., 2024). A growing body of literature also explores the macroeconomic and financial dimensions of energy poverty, linking it to broader issues such as economic growth, income inequality, poverty, and financial development (Doğanalp et al., 2021; Igawa and Managi, 2022; Singh and Inglesi-Lotz, 2020; Ullah et al., 2021). These studies underscore the role of structural economic factors in shaping the vulnerability of households to energy.

Although official definitions of energy poverty remain elusive, this study adopts a widely accepted conceptualization: the inability of households to access or afford the energy services necessary for basic needs such as cooking, heating, cooling and lighting at levels that support a minimum standard of living (Bouzarovski, 2018; Robić and Ančić, 2018; Teschner et al., 2020). Importantly, energy poverty is not only a matter of consumption or affordability. It also encompasses issues of availability, reliability, affordability, acceptability, quality, and safety of energy infrastructure and appliances, reflecting its deeply embedded nature in both economic systems and social structures.

2.2. Empirical Literature

Empirical studies have increasingly highlighted the critical role of renewable energy technologies and rural electrification in addressing energy poverty and promoting socio-economic development. Zubi et al. (2019) empirically examine the relationship between rural solar photovoltaic (PV) electrification and poverty, concluding that decentralized solar photovoltaic systems contribute significantly to alleviating energy poverty in rural areas. This finding is supported by Pereira et al. (2010), who, using a large-scale household survey in Brazil, report a reduction in energy poverty from 37% to 26% between 2000 and 2004 because of rural electrification initiatives. In the Chinese context, Liao and Fei (2019) and Li et al. (2020) find that flexible PV-based interventions have a measurable impact on poverty alleviation in remote rural regions. However, Geall and Shen (2018) caution that such interventions may not uniformly improve living standards, particularly among nomadic populations.

The transition to renewable energy sources has also been shown to significantly reduce energy poverty. Zhao et al. (2022), employing heterogeneous panel data analysis, found that renewable energy adoption has a statistically significant negative effect on global energy poverty, with energy efficiency serving as a mediating factor. Biernat-Jarka et al. (2021) provide complementary evidence from Poland, where government investments in renewable energy between 2010 and 2018 led to a gradual but observable decline in energy poverty. Similarly, Zhang et al. (2020) confirm the positive and significant impact of photovoltaic investment on poverty reduction in China. Beyond renewable energy, other studies emphasize the importance of energy consumption patterns, infrastructure, and institutional quality, such as Dong et al. (2021) who used provincial panel data from

China spanning 2004 to 2017. They showed that increased natural gas consumption reduces energy poverty through improvements in energy services, consumption behaviour, institutional frameworks, and energy efficiency. Okwanya and Abah (2018) argue that to maximize the poverty reducing effects of energy consumption, governments in 12 African countries must invest in energy infrastructure and ensure political stability. Chirambo (2018) supports this view, asserting that electrification can stimulate economic growth, reduce youth unemployment, and alleviate inequality in Sub-Saharan Africa.

Khan and Ghardallou (2023) conducted an empirical investigation into the role of human capital in mitigating energy poverty within emerging economies. Using a comprehensive panel dataset comprising 108 developing countries during the period 2000 to 2019, the study employed dynamic ordinary least squares (DOLS) estimation techniques to assess the relationship between education and energy access. The findings reveal a statistically significant and positive association between educational attainment and access to electricity, suggesting that improvements in human capital contribute significantly to reducing energy poverty in the sample economies.

The broader developmental implications of energy poverty are also well documented; for example, Adom et al. (2021) examined the short- and long-term effects of energy poverty and the transition to renewable energy on development outcomes in Ghana. Their findings indicate that energy poverty negatively affects income, education, life expectancy, employment, and access to communication technologies, while exacerbating poverty, inequality, and exposure to unsafe water. However, the adoption of renewable energy partially compensates for these adverse effects, highlighting its role as a compensatory mechanism. In a similar vein, Mboumboue and Njomo (2016) emphasize that energy access improves living standards and contributes to both social and economic development, underscoring the multifaceted role of energy in advancing human welfare.

Given the conceptual and empirical complexities surrounding energy poverty, this study is motivated by the urgent need to address persistent energy deprivation prevalent in SSA. The region exhibits severe infrastructure deficiencies, elevated poverty levels, and limited access to modern energy services, positioning it as one of the most energy-poor areas in the world. Empirical studies from various economies such as China, Brazil and Poland demonstrate that RETs particularly decentralized solutions such as PV systems, can significantly mitigate energy poverty. However, the applicability of these findings to SSA remains uncertain due to region-specific structural constraints, including political instability, weak institutional governance, and underdeveloped energy infrastructure.

Thus, this study seeks to conduct a targeted analysis of how renewable energy interventions can be adapted to the distinct socio-economic and geographic contexts of the SSA while assessing their efficacy in alleviating structural determinants of energy poverty. The findings will provide critical information for policy makers, investors, and development professionals, facilitating evidence-based strategies to improve energy access and advance SDGs 7 in the region.

3. METHODOLOGY

3.1. Methodology and Data Specifications

This study empirically investigates the relationship between renewable energy consumption and energy poverty alleviation across 43 SSA countries over the period 2002-2021. In line with the conceptual and methodological gaps identified in the literature, a dynamic panel data approach is adopted to account for the persistence of energy poverty and to address potential endogeneity arising from the bidirectional relationship between renewable energy deployment and energy access outcomes. The dynamic structure of the model incorporates a lagged dependent variable to reflect the influence of past energy poverty levels on current conditions. To estimate the model, the study employs a two-step system GMM estimator, following the Arellano and Bover (1995) and Blundell and Bond (1998) framework. This estimator is particularly well-suited for panels with a relatively small-time dimension and a larger cross-sectional dimension, as is typical in cross-country studies. It effectively controls for unobserved country-specific effects, corrects for potential endogeneity of explanatory variables, and mitigates autocorrelation in the error term. The model specification includes standard instruments in the level equation and applies a robust two-step estimator with finite-sample correction for standard errors to improve efficiency and reliability.

To ensure the validity of the instrument set and the robustness of the estimation results, the study conducts the Hansen test for overidentifying restrictions and the Arellano-Bond tests for first order and second-order serial correlation in the differenced residuals. These diagnostic tests confirm the appropriateness of the instrument set and the reliability of the estimator, thereby strengthening the credibility of the causal inferences drawn from the analysis. The remaining explanatory variables are assumed to be exogenous and are included as standard instruments in the level equation.

Energy poverty is operationalized as the percentage of the population that lacks access to electricity, derived from the World Bank's access to electricity index. This measure is preferred over the Multidimensional Energy Poverty Index (MEPI), which, despite its comprehensiveness, is constrained by limited data availability, inconsistency, and lack of comparability across African countries. The study integrates a set of control variables informed by the literature, including GDP per capita (as a proxy for economic development), population density (to capture demographic pressure on infrastructure), institutional quality (measuring governance effectiveness, regulatory quality, and political stability), and the Human Capital Index (reflecting education and health outcomes). These variables are sourced from the World Bank's (2025) World Development Indicators, UNCTAD (2025), and Quantec databases.

The empirical model is estimated using a two-step system Generalized Method of Moments (GMM) estimator, which is appropriate for addressing endogeneity and unobserved heterogeneity in dynamic panel settings. The dataset covers 43 SSA countries, including Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Côte d'Ivoire, Equatorial Guinea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Tanzania, Togo, Uganda, Zambia, and Zimbabwe. The study period ends in 2021 due to the inaccessibility of consistent data for key variables beyond that year.

3.2. Model Specification

This study follows the work of Zhao et al. (2022) and Kocak et al. (2023) and uses the two-step System Generalized Method of Moments (GMM) approach. The research model for this study is as follows.

$$Energy\ Poverty_{it} = \alpha + Energy\ Poverty_{it-1} + \beta_1\ Renewable\ Energy_{it} + \beta_2\ GDPC_{it} + \beta_3\ Population\ density_{it} + \beta_4\ Institutions_{it} + v_i + n_t + \varepsilon_{it} \quad (1)$$

$i = 1.,44;\ t = 2002,\ldots,2021$

In the specified empirical model, the subscripts i and t denote the cross-sectional unit (country) and the temporal dimension (year), respectively. The dependent variable, Energy Poverty (EP), is quantified as the percentage of the population without access to electricity. The lagged term, EP_{it-1}, captures the persistence of energy poverty over time. The variable RE represents the consumption of renewable energy, while GDPC serves as a proxy for economic development, measured by per capita income. Population Density (PD) is defined as the number of individuals per square kilometre, and Institutional Quality (IN). The UNCTAD (2025) institutional quality index is designed to assess political stability and governance effectiveness by evaluating dimensions such as regulatory quality, institutional effectiveness, success in combating crime, corruption, and terrorism, as well as the protection of citizens' freedoms of expression and association. The parameter α_0 represents the constant term. The stochastic error term is denoted by ε_{it}, while v_t captures time-specific effects common across countries, and η_i accounts for unobserved time-invariant heterogeneity across countries.

3.3. Estimation Strategy

This study employs a dynamic panel data framework to rigorously assess the causal impact of renewable energy on mitigating energy poverty in Sub-Saharan Africa, utilizing the two-step System GMM (Arellano and Bover, 1995; Blundell and Bond, 1998). This estimator is particularly well-suited for datasets with a large cross-sectional dimension (N) and a relatively short time dimension (T), a common structure in macroeconomic and development studies using country level data.

The dynamic specification incorporates a lagged dependent variable to account for the persistence of energy poverty over time, recognizing that past deprivation levels influence current outcomes. However, the inclusion of a lagged dependent variable introduces endogeneity due to its correlation with the error term, rendering conventional estimators such as Ordinary Least Squares (OLS) and Fixed Effects (FE) biased and inconsistent (Nickell, 1981). To address these econometric challenges, the two-step System GMM estimator employs internal instruments derived from lagged levels and differences of the endogenous regressors, effectively mitigating endogeneity, measurement error, and unobserved country-specific heterogeneity. The two-step variant of the estimator is preferred for its efficiency gains, as it uses residuals from the first step to construct a robust variance-covariance matrix, with the Windmeijer (2005) finite-sample correction applied to correct for potential downward bias in standard errors. The validity of the instruments is assessed using the Hansen J-test for overidentifying restrictions, while the Arellano-Bond tests for first-order AR (1) and second-order AR (2) serial correlation in the differenced residuals ensure the consistency of the estimator. A non-significant AR (2) result serves as a key diagnostic.

Following Favara (2003), the assumption of homoscedastic and serially uncorrelated errors is relaxed in the two-step estimation, allowing for more robust inference. The two-step System GMM offers a robust empirical strategy for estimating the dynamic and potentially endogenous relationship between renewable energy deployment and energy poverty, while effectively addressing unobserved heterogeneity and ensuring valid inference through rigorous diagnostic checks.

4. RESULTS

4.1. Descriptive Statistics

Table 1 presents the summary statistics for the key variables employed in the empirical analysis, offering information on their distributional properties and cross-sectional variability.

Energy poverty (EP) has a mean value of 59.89%, accompanied by a substantial standard deviation of 26.20. The observed range spans from 0% to 98.7%, underscoring pronounced heterogeneity in energy access across countries and over time. These figures reflect significant disparities in infrastructural development and energy provision within the region. Renewable energy (RE) consumption demonstrates considerable distribution. The mean value stands at 65.75%, with a standard deviation of 26.84. The minimum and maximum values 0.7% and 98.3% suggest a wide spectrum of renewable energy integration, ranging from near total reliance to minimal adoption. GDP per Capita (GDPC) has a mean of 1.69 and a relatively high standard deviation of 4.76. The range extends from −36.83 to 30.02, with this variation

Table 1: Descriptive statistics

Variable	Observation	Mean	Standard deviation	Min	Max
EP	860	59.89	26.198	0	98.7
RE	860	65.75	26.84	0.7	98.3
GDPC	860	1.69	4.76	-36.83	30.02
PD	860	101.20	129.85	2.296	634.12
IN	860	41.60	13.87	1	75.4
HCI	860	23.32	8.875	3.2	49.2

reflecting the economic volatility and divergent income levels characterizing the sample countries. Population density (PD) averages 101.20, with a standard deviation of 129.85. The maximum value of 634.12 indicates that certain countries exhibit markedly higher population concentrations, which may have implications for infrastructure demand and energy distribution. Institutional quality (IN) yields a mean score of 41.60 and a standard deviation of 13.87. This suggests moderate variation in governance effectiveness and institutional performance, factors that are likely to influence energy policy implementation and economic outcomes. Human capital (HCI) has a mean of 23.32 and a standard deviation of 8.88. The index ranges from 3.2 to 49.2, indicating substantial disparities in human capital development. These differences are critical for understanding the capacity of populations to engage with and benefit from modern energy services.

4.2. Correlation Analysis

The correlation matrix IN Table 2 yields several economically significant relationships between key variables. Energy poverty (EP) demonstrates a robust positive association with renewable energy consumption (RE) (r = 0.66), a counterintuitive result that may indicate suboptimal targeting of renewable investments or insufficient penetration in energy-deprived regions. In contrast, EP shows a strong negative correlation with the Human Capital Index (HCI) (r = −0.69), consistent with theoretical expectations that education and health improvements enhance energy access. Moderately negative correlations emerge between EP and institutional quality (IN) (r = −0.44) as well as population density (PD) (r = −0.27), aligning with the hypothesis that governance capacity and agglomeration effects facilitate electrification. RE exhibits significant negative correlations with both IN (r = −0.63) and HCI (r = −0.58), suggesting that renewable deployment may be disproportionately concentrated in institutionally weaker areas of lower-human-capital. These patterns underscore the multidimensional nature of energy poverty determinants, where structural factors (institutions, human capital) and energy system characteristics (renewable penetration density) interact in non-trivial ways. The results warrant further investigation through causal economic analysis to unravel supply-side constraints from demand-side adoption barriers in the SSA energy transition.

4.3. Results of GMM

The empirical estimates presented in Table 3, obtained through a dynamic panel framework utilizing the two-step System GMM estimator, provide critical evidence on the underlying drivers of energy poverty across the sample countries. The models incrementally incorporate variables from stages (1) through (5) into the baseline specification.

Table 2: Correlation matrix

Variable	EP	RE	GDPC	PD	IN	HCI
RE	0.6609					
GDPC	0.0451	0.0494				
PD	−0.2669	−0.1513	0.0394			
IN	−0.4369	−0.6289	0.0668	0.2532		
HCI	−0.689	−0.5771	−0.0567	0.4446	0.6476	

The coefficient on the lagged dependent variable, EP_{t-1} is both positive and highly statistically significant in all models, indicating a strong degree of persistence in energy poverty over time. This suggests that countries experiencing elevated levels of energy poverty in prior periods are likely to continue exhibiting similar conditions in subsequent periods. This persistence reflects structural inertia in energy access, often rooted in historical underinvestment in energy infrastructure. These findings align with Drescher and Janzen (2021), who demonstrate that regions experiencing energy poverty in one period exhibit a significantly higher probability of remaining energy poor in subsequent periods. The magnitude of the autoregressive coefficient underscores the entrenched nature of energy poverty, particularly in SSA, where legacy inequalities in infrastructure provision continue to shape contemporary access outcomes. This persistence implies that short-term policy interventions may be insufficient, and that long-term, sustained investment strategies are essential to break the cycle of deprivation.

Unexpectedly, the coefficient on renewable energy consumption (RE) is positive and statistically significant across all models, decreasing from (0.190) to (0.114) suggesting that increases in renewable energy deployment are associated with a marginal rise in energy poverty. The coefficient diminishes with the inclusion of additional control variables, indicating that the observed relationship is partially explained by other underlying factors. This counterintuitive result may reflect the limited scale, geographic targeting, or integration of current renewable energy initiatives, which may not yet be effectively reaching marginalized or off-grid populations. It raises concerns about the inclusivity of the energy transition and suggests that without deliberate policy design,

Table 3: Results of GMM

Variables	(1) Model 1	(2) Model 2	(3) Model 3	(4) Model 4	(5) Model 5
EP_{t-1}	0.698***	0.701***	0.701***	0.702***	0.757***
	(0.113)	(0.108)	(0.109)	(0.110)	(0.0787)
RE	0.190***	0.190***	0.182***	0.169**	0.114**
	(0.0701)	(0.0677)	(0.0662)	(0.0672)	(0.0443)
GDPC		−0.0280	−0.0218	−0.0170	−0.0515
		(0.0514)	(0.0532)	(0.0542)	(0.0433)
PD			−0.00716	−0.00641	−0.00216
			(0.00781)	(0.00764)	(0.00633)
IN				−0.0447	0.100
				(0.0833)	(0.0736)
HCI					−0.393**
					(0.174)
Year	−0.284**	−0.280**	−0.268**	−0.271**	0.00426
	(0.131)	(0.119)	(0.120)	(0.122)	(0.0745)
Constant	575.8**	566.7**	543.3**	552.7**	2.577
	(266.0)	(241.6)	(244.8)	(248.3)	(147.7)
Diagnostic tests					
Sargan test	0.002***	0.002***	0.003***	0.003***	0.000***
Hansen test	0.317	0.330	0.322	0.323	0.231
AR (1)	0.000***	0.000***	0.000***	0.000***	0.000***
AR (2)	0.738	0.739	0.735	0.717	0.748
Observations	817	817	817	817	817
Number of CountryID	43	43	43	43	43
Instruments	22	23	24	25	26

Standard errors in parentheses ***P<0.01

renewable energy expansion may not automatically translate into improved energy access for the poor. This finding differs from the theoretical expectations that increases in renewable energy results in a decrease in energy poverty (Biernat-Jarka et al., 2021; Kocak et al., 2023; Liao and Fei, 2019; Zhang et al., 2020; Zubi et al., 2019). However, these findings are consistent with those of Geall and Shen (2018), who reported that the deployment of improved solar energy systems had no statistically significant impact on the living standards of many nomadic households in China.

The estimated coefficients for GDP per capita and institutional quality (IN) were negative and positive, respectively; however, neither variable exhibited statistical significance at conventional levels. These findings suggest that economic growth, in isolation, does not necessarily translate into improved energy access, thereby underscoring the importance of targeted renewable energy policies. The lack of significance for institutional quality may be attributable to limitations in measurement or the prevalence of informal energy markets within SSA which may obscure formal institutional effects.

Similarly, population density (PD) and the time trend variable did not exert statistically significant effects on energy poverty. The insignificance of PD implies that energy poverty is not confined to rural areas, as urban slums and peri-urban settlements also experience substantial deficits in electricity access. The null effect of the time trend further indicates that energy poverty in SSA has not shown automatic improvement over time, reinforcing the necessity for proactive and sustained policy interventions.

In contrast, the Human Capital Index (HCI) demonstrated a negative and statistically significant relationship with energy poverty in model (5), suggesting that improvements in human capital play a critical role in facilitating access to modern energy services. This result aligns with the findings of Khan and Ghardallou (2023), who establish a positive association between educational attainment and electricity access. The implication is that integrated development strategies that combine energy infrastructure with human capital investments may yield more effective outcomes in addressing energy poverty.

The diagnostic tests conducted across all five GMM models affirm the robustness and consistency of the estimations. The Arellano-Bond test for first-order autocorrelation AR (1) yielded statistically significant results in all models ($P < 0.001$), indicating the presence of expected serial correlation in the differenced residuals. Conversely, the test for second-order autocorrelation AR (2) was consistently insignificant with p-values ranging from (0.717) to (0.748), suggesting the absence of second-order serial correlation (Arellano and Bond, 1991). The Sargan test indicated potential concerns in some specifications. However, the Hansen test, which is robust to both heteroskedasticity and autocorrelation, remained statistically insignificant across all models with p-values ranging from (0.231) to (0.330). This supports the validity of the instruments employed and reinforces the reliability of the two-step system GMM estimator used in the analysis (Blundell and Bond, 1998; Roodman, 2009). Given its robustness, the Hansen test is considered the more appropriate diagnostic in this context. Collectively, these results confirm that the GMM estimators are well-specified and that the instruments used are valid, lending credibility to the empirical findings on the determinants of energy poverty in Sub-Saharan Africa.

5. DISCUSSION

The empirical findings of this study provide several important insights into the structural dynamics of energy poverty and the evolving role of renewable energy in Sub-Saharan Africa (SSA). The statistically significant and positive coefficient on the lagged dependent variable confirms the high degree of persistence in energy poverty throughout the region. This result suggests that countries experiencing elevated levels of energy deprivation in previous periods are likely to remain energy-poor in subsequent periods, reflecting deep-rooted infrastructural and institutional constraints. This persistence is indicative of path dependency on energy access outcomes, where historical underinvestment in energy infrastructure continues to shape current disparities. This aligns with the findings of Blimpo and Cosgrove-Davies (2019), who argue that regions with chronic electricity deficits face difficulties in attracting private investment, thus perpetuating cycles of energy inequality. These results underscore the need for long-term, structural interventions that address both historical legacies and systemic barriers to energy access. Policy frameworks must move beyond short-term electrification targets and instead adopt integrated development strategies that incorporate energy planning with broader socio-economic objectives, particularly those aimed at enhancing human capital.

The positive and statistically significant coefficient on renewable energy consumption presents a counterintuitive outcome, diverging from the theoretical expectation that increased deployment of renewable energy should reduce energy poverty. One plausible explanation is that renewable energy investments in SSA are not being equitably distributed. Rather than targeting the most energy-deprived populations, such investments may be concentrated in urban or peri-urban areas where grid infrastructure already exists, or they may be supplementing existing energy sources without expanding access. This finding suggests that, while expansion of renewable energy has considerable potential to expand energy access, its current deployment may not be insufficiently inclusive or poorly aligned with the spatial distribution of energy poverty. The modest effect size further implies that the scale of renewable energy adoption remains inadequate to generate transformative outcomes. This supports the argument advanced by Ondraczek (2013), who emphasizes the effectiveness of decentralized solar systems in rural areas where grid extension is economically unviable. However, the realization of this potential requires substantial scaling-up of investments and improved policy coordination. The positive association observed may also reflect implementation challenges such as high upfront costs, limited infrastructure, and weak institutional support, which restrict the ability of renewable energy supply to reach underserved communities. Additionally, the result may capture a temporal lag between renewable energy investments and their eventual impact on energy access, particularly in regions where deployment is still in its early stages.

The study also finds a strong and statistically significant negative relationship between the Human Capital Index (HCI) and energy poverty, highlighting the critical role of education and health in facilitating access to modern energy services. Households with higher levels of education are more likely to adopt and maintain renewable energy technologies and to advocate for improved energy services (Dagnachew et al., 2020). This finding reinforces the argument for integrating energy access initiatives with broader human development programs. Investments in education, vocational training, and public health not only enhance the absorptive capacity of communities but also contribute to the sustainability of energy interventions. Evidence suggests that human capital development can serve as a complementary pathway to reducing energy poverty, particularly when aligned with decentralized energy strategies.

In contrast, GDPC and institutional quality (IN) were statistically insignificant, suggesting that macroeconomic growth and governance improvements alone do not guarantee reductions in energy poverty. This finding is consistent with the literature that emphasizes the need for inclusive growth and targeted policy interventions (Apergis et al., 2022). Economic expansion may not translate into improved energy access if it is not accompanied by deliberate efforts to extend infrastructure and services to marginalized populations. Similarly, while institutional quality is generally associated with better development outcomes, its direct effect on energy poverty may be mediated through specific policy instruments and implementation mechanisms, which were not explicitly captured in this analysis.

Finally, the insignificance of population density (PD) and the time trend provide additional insight into the spatial and temporal dimensions of energy poverty in SSA. The lack of a significant relationship with population density suggests that energy deprivation is not limited to rural areas, but also affects urban and peri-urban communities, particularly informal settlements. This finding calls for geographically inclusive energy policies that address access disparities in both urban and rural contexts. Moreover, the absence of a statistically significant time trend indicates that energy poverty is not declining autonomously over time, reinforcing the need for sustained and proactive policy interventions.

6. CONCLUSION

This study provides robust empirical evidence on the relationship between renewable energy and energy poverty in SSA offering critical insights into the structural and policy dimensions of energy access. The results demonstrate that energy poverty in the region is highly persistent, reflecting deep-rooted infrastructural deficits and historical underinvestment. This persistence implies that short-term interventions are unlikely to yield transformative outcomes, and that long-term, systemic strategies are essential to break the cycle of deprivation.

Although the deployment of renewable energy is widely promoted as a solution to energy poverty, the study reveals a counterintuitive positive association between renewable energy consumption and energy poverty. This suggests that current renewable energy initiatives may not be adequately reaching the most energy-deprived populations. Investments appear to be concentrated in urban or grid-connected areas, with limited penetration in rural and peri-urban communities where energy poverty is most acute. The modest effect size further indicates that the scale and targeting of renewable energy programs remain insufficient to have meaningful impact. These findings underscore the need for deliberate policy design that ensures equitable distribution of renewable energy infrastructure, particularly through decentralized systems such as off-grid and mini-grid solutions.

The significant negative relationship between the Human Capital Index (HCI) and energy poverty highlights the critical role of education, health, and skills development in facilitating access to modern energy services. Educated and healthy populations are more likely to adopt and maintain renewable energy technologies, suggesting that energy access initiatives should be integrated with broader human development programs. This supports the argument for multi-sectoral approaches that combine energy planning with investments in education and vocational training to enhance local capacity and sustainability.

In contrast, the study does not find statistically significant effects for GDP per capita, institutional quality, population density, or time trends. These results challenge the assumption that economic growth and governance improvements alone are sufficient to reduce energy poverty. Instead, they point to the need for targeted energy policies that explicitly address access disparities and prioritize inclusivity. The insignificance of population density further suggests that energy poverty is not confined to rural areas but also affects urban and peri-urban populations, necessitating geographically inclusive strategies. In addition, the absence of a declining trend over time reinforces the urgency of proactive and sustained policy interventions.

These findings have important implications for the achievement of Sustainable Development Goal 7 (SDG 7), which aims to ensure access to affordable, reliable, sustainable and modern energy for all. Although renewable energy capacity is expanding in SSA, the current trajectory suggests that the region remains off-track to meet SDG 7 targets. Without targeted delivery mechanisms and inclusive financing models, an estimated 600 million people may still lack access to electricity by 2030. Accelerating progress will require a paradigm shift from viewing energy access as a purely technical challenge to recognizing it as a multidimensional development issue.

Several policy recommendations emerge based on these conclusions. First, renewable energy deployment must be reoriented to prioritize underserved areas through decentralized solutions, supported by pro-poor financing mechanisms such as pay-as-you-go systems and targeted subsidies. Second, energy access programs should be integrated with education and vocational training initiatives to build local capacity for technology adoption and maintenance. Third, policy frameworks should move beyond generic economic growth strategies to include specific targets and metrics to reduce energy poverty. Fourth, governments and development partners should establish robust monitoring and evaluation systems that capture not only electrification rates but also the quality, reliability, and affordability of energy access in different demographic groups. Finally, community-based energy models and long-term structural reforms must be adopted to ensure that renewable energy investments translate into meaningful and lasting reductions in energy poverty.

Despite its contributions, this study is subject to certain limitations. The use of national-level data may obscure subnational disparities in energy access, particularly between urban and rural areas. Additionally, the analysis relies on aggregate measures of renewable energy consumption, which do not differentiate between technology types or deployment models. Future research should explore disaggregated data at the regional or household level to capture localized dynamics more accurately. In addition, examining the role of specific renewable energy technologies and incorporating qualitative assessments of policy implementation could provide a more nuanced understanding of the mechanisms through which renewable energy affects energy poverty. Longitudinal case studies and mixed-methods approaches would further enrich the empirical evidence base and inform more targeted and context-sensitive policy interventions.

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