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Does Energy Poverty Hinder Human Capital Development in Sub-Saharan Africa?

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Abstract

This study examines the relationship between energy poverty and human capital development across 46 Sub-Saharan African countries from 2000 to 2023. Employing panel cointegration techniques and an Autoregressive Distributed Lag (ARDL) Error Correction Model (ECM), the analysis controls for key socioeconomic and institutional factors, including GDP per capita, urbanisation, government effectiveness, and population growth. Results reveal a significant long-run adverse effect of energy poverty on human capital, highlighting the detrimental impact of inadequate access to modern energy on education and health outcomes. Government effectiveness emerges as a positive driver of human capital, reinforcing the role of institutional quality in this regard. While the short-run effects of energy poverty are statistically insignificant, the error correction term confirms a strong adjustment towards the long-run equilibrium. Robustness checks, which address cross-sectional dependence and heteroskedasticity, validate the stability of the findings. These results underscore the critical importance of addressing energy deprivation alongside improving governance to foster sustainable human capital development in Sub-Saharan Africa.

Keywords: Energy poverty, Government effectiveness, Human capital index, Panel ARDL, Sub-Saharan Africa.

1. Introduction

Energy poverty, conceptualised as the lack of access to modern, reliable, and affordable energy services, remains a pervasive challenge in Sub-Saharan Africa (SSA). As of 2024, over 600 million people in Africa lack access to electricity, with the majority residing in Sub-Saharan Africa (SSA) (UNCTD, 2023). This deficiency hampers various aspects of human development, including education, health, and economic growth (Adeodun, 2024; Ayuk, 2023). The reliance on traditional biomass fuels for cooking, such as wood and charcoal, not only contributes to deforestation but also exposes households to harmful indoor air pollution. The World Health Organisation estimates that such pollution results in approximately 600,000 deaths annually in Africa (UNEP, 2016). Moreover, the absence of electricity in schools impedes educational outcomes, as students are unable to study after dark, and schools lack the necessary infrastructure to support modern teaching methods (Timilsina & Malla, 2021).

Energy poverty in Sub-Saharan Africa arises from a complex interplay of infrastructural, economic, policy, and geographic factors. A significant contributor to this issue is the inadequate energy infrastructure, much of which dates back to the colonial era and was primarily designed to support extractive industries rather than serve local populations (Michoud & Hafner, 2021). Following independence, many governments faced financial constraints and political instability, resulting in underinvestment in rural electrification and the maintenance of existing infrastructure (IMF, 2008; Mekonnen & Hailu, 2023; Alenoghena et al., 2020). Extending electrical grids to remote areas is particularly costly, and many nations lack the financial capacity to undertake such expansive projects.

The International Energy Agency estimates that Africa will require over $190 billion annually to achieve universal electricity access by 2030 (ENA, 2024). Approximately 600 million people in Africa lack access to electricity, with the majority residing in Sub-Saharan Africa. This lack of reliable energy access severely hampers the functionality of healthcare facilities. For instance, only 28% of health facilities in Sub-Saharan Africa have reliable electricity, which is essential for powering medical equipment, lighting, and refrigeration necessary for storing vaccines and medicines (AEC, 2023).

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Economic challenges further exacerbate energy poverty. High electricity generation costs, often two to three times the global average, make energy services unaffordable for many (Copinschi, 2022). This is due to factors such as the small scale of national power systems and reliance on expensive, oil-based generation methods. Additionally, the lack of comprehensive national energy policies, regulatory barriers, and issues like corruption hinder the development and expansion of energy access initiatives (ENA, 2024). Geographic factors also influence energy poverty. Many communities are located in remote areas where extending the national grid is logistically challenging and economically unviable. As a result, these communities often rely on traditional biomass fuels, such as wood and charcoal, for cooking and heating, which not only pose health risks but also contribute to environmental degradation (Agoundedemba et al., 2023; Japinye et al., 2025).

Energy poverty also exacerbates gender inequalities (Butty et al., 2024). Women and girls often bear the responsibility of collecting fuel, a time-consuming task that limits their opportunities for education and employment. Furthermore, the lack of energy access hinders the operation of healthcare facilities, affecting maternal and child health services (Adeodun, 2024). Despite the critical role of energy in human capital development, investments in energy infrastructure in sub-Saharan Africa (SSA) remain insufficient. The International Energy Agency estimates that achieving universal access to electricity in Africa by 2030 would require annual investments of over $190 billion (IEA, 2022). However, current funding levels fall short, and the region continues to face challenges related to infrastructure, policy, and financing.

Human capital development, encompassing education, health, and skills, is fundamental to economic growth and poverty reduction (Carabajal, 2024; Alenoghena et al., 2025). In SSA, energy poverty presents a significant barrier to enhancing human capital. The lack of access to reliable and affordable energy services impedes educational attainment, health outcomes, and overall well-being (UNESCO, 2024). Educational institutions without electricity struggle to provide quality education, and students in households without lighting are disadvantaged in their studies. Health facilities lacking power cannot operate essential equipment, affecting the delivery of healthcare services (WHO, 2023). Moreover, the burden of energy collection disproportionately affects women and girls, limiting their participation in education and the workforce (Patrice et al., 2024)

Despite the growing body of literature on energy poverty and development in Sub-Saharan Africa (SSA), several critical gaps remain that limit a comprehensive understanding of how energy deprivation affects human capital development. First, there is a notable lack of integrated empirical studies that directly examine the relationship between energy poverty and human capital development as a holistic concept. Most existing research tends to address either the educational or health dimensions in isolation without recognising their interrelatedness within the broader framework of human capital (Sule et al., 2022; Ndiaye & Diouf, 2024; Adebisi et al., 2025).

This study is organised into seven key sections. Following this introductory chapter, Section Two provides a comprehensive review of the relevant empirical literature. Section Three outlines the theoretical framework underpinning the study. Section Four details the research methodology and model specification employed in the analysis. In Section Five, the nature and sources of the data are described. Section Six presents and discusses the empirical results. Finally, Section Seven concludes the study with a summary of key findings and offers policy recommendations based on the results.

2. Review of Empirical Literatures

Yang et al. (2025) investigated the impact of energy poverty on child development in rural China, with a specific focus on cognitive outcomes. Using a dynamic framework, the authors construct an index to measure household vulnerability to energy poverty. Employing empirical analysis, the study finds that such vulnerability significantly hampers children's cognitive ability, with the effect more pronounced in low-income households and among girls. Years of schooling are identified as a mediating variable, suggesting that access to education moderates this relationship. Based on these findings, the authors recommend macro-level policy interventions to reduce rural energy poverty and enhance child well-being. The model could be strengthened by including institutional and infrastructural variables. Nonetheless, the study effectively bridges energy policy with concerns about human capital development.

Dong and Xu (2025) addressed the complex nature of energy poverty in China by constructing a Multidimensional Energy Poverty Index (MEPI) incorporating energy use level, structure, and capacity. It employs a spatial Durbin model to analyse the impact of MEPI on regional social welfare, as measured by the Development and Living Index (DLI). The results reveal that energy poverty negatively affects the welfare of both local and neighbouring regions, with the level of energy use showing the most substantial spillover effects. The study's applicability may be limited to contexts with similar data infrastructure and policy environments. Furthermore, the impact of informal regulation and innovation is noted but underexplored. Still, it offers a strong case for integrated, regional policy coordination in addressing energy poverty.

Maket (2025) examined the gendered impacts of energy poverty in Kenya, focusing on the health outcomes of women. Employing the Alkire-Foster method, the authors calculate the multidimensional incidence and intensity of energy poverty. Using 2022 Kenya Demographic and Health Survey (KDHS) data, they employ a two-part cross-county modelling approach to analyse the energy-health nexus. The results show that energy poverty significantly worsens women's self-reported health and increases overall health deprivation. The study highlights the disproportionate burden energy poverty places on women in traditional rural settings. It effectively addresses endogeneity concerns, strengthening the validity of the findings. Based on the evidence, the authors recommend urgent, region-specific policy interventions that target energy access and women's health. Their analysis makes a significant contribution to the gender-sensitive energy policy discourse. However, the study would benefit from comparative analysis with male health outcomes to enhance the gender contrast.

Leal Filho et al. (2025) investigated the pervasive issue of energy poverty in Latin America, where inadequate energy systems exacerbate poverty and hinder economic development. Using bibliometric analysis and survey methods, the research identifies structural deficiencies in energy access as a significant barrier to achieving the UN Sustainable Development Goals (SDGs). The findings highlight that a large portion of household income is spent on energy, stressing the economic burden on low-income families. The study contributes valuable policy insights

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and underscores the need for systemic reforms in energy infrastructure across developing regions. The work aligns energy access with both climate goals and poverty reduction strategies.

Liang et al. (2025) investigated the causal impact of education on household energy poverty and energy justice in China using the 1986 Compulsory Education Law as an exogenous shock and data from the China Family Panel Survey. Results indicate that each additional year of education decreases the likelihood of energy poverty by 2.3%, primarily through enhanced human capital returns and eased borrowing constraints. The effect is more pronounced among disadvantaged groups, including women and rural residents, highlighting the role of education in promoting energy justice. These findings underscore the importance of education as a key tool for reducing energy poverty and promoting equitable energy access. The study provides robust evidence for policymakers to integrate education strategies into their efforts to alleviate energy poverty. However, further research could examine the long-term socio-economic impacts across different regions.

Nsenkyire et al. (2024) investigate the impact of multidimensional energy poverty on women's well-being in Sub-Saharan Africa, using data from the MICS 6 survey across three West African countries. Employing structural equation modelling (SEM) and seemingly unrelated regression (SUR), the authors find that energy poverty significantly undermines women's subjective well-being and cognitive health. The study reveals a mediating relationship in which diminished well-being has an adverse effect on cognitive health outcomes. It highlights the gendered consequences of energy deprivation, particularly in societies where domestic roles are primarily female-driven. Its policy recommendation emphasises the importance of improving access to modern energy services to enhance women's health and household efficiency. However, the study could be enhanced by including longitudinal data to assess long-term impacts.

Kumar et al. (2024) explored the determinants of energy poverty (EP) in BRICS countries, using panel data spanning from 1990 to 2022. Applying robust panel regression and causality models, the authors examine how factors such as income inequality (IEQ), energy intensity (EI), and macroeconomic indicators influence energy poverty (EP). Results show that IEQ and EI worsen EP, while FDI, GDP, trade openness (TRD), and government spending (GS) help reduce it. Panel causality analysis reveals bidirectional links between EP and FDI, IEQ, and EI, with GDP and TRD showing unidirectional causality. The study's broad temporal scope and model robustness strengthen its policy relevance. It recommends targeted welfare initiatives and enhanced international collaboration to mitigate EP. By aligning with SDG 7, it offers actionable insights for achieving sustainable energy access. However, the inclusion of disaggregated regional data within BRICS could improve the granularity of policy guidance.

Liu and Hu (2024) investigated the impact of household energy consumption (HEC) on health shocks using data from the 2018 China Health and Nutrition Survey (CHNS). Employing regression and instrumental variable models, the authors assess both linear and nonlinear relationships between HEC, health, poverty, and living conditions. Results show that increased HEC reduces self-reported health shocks by 64%, with low-income households experiencing the most significant health risks. Poor households benefit more from cleaner energy consumption, as increased energy use significantly lowers the risk of critical illness. The study reveals a U-shaped relationship between income levels and health benefits, with middle-income groups experiencing the most significant benefits. It concludes that energy inequality is a critical driver of health disparities. Recommendations include advancing household energy structures and targeting energy poverty alleviation policies. However, the study could further benefit from a comparative analysis across different geographic regions or urban-rural contexts.

Ding et al. (2024) examined the influence of agricultural financing, energy poverty, human capital, and corruption on child and maternal malnutrition in nine West African countries from 1990 to 2019. Utilising second-generation panel econometric techniques and the Method of Moments Quantile Regression (MMQR), the authors assess the determinants of malnutrition within the context of the Sustainable Development Goals (SDGs). The results show that agricultural credit and foreign aid reduce malnutrition, while agricultural research spending unexpectedly increases it. Energy poverty and low human capital are significant contributors to higher malnutrition rates, while corruption exacerbates this issue. The study highlights the interconnectedness of energy access, education, and governance in improving nutrition outcomes. It advocates for integrated policies supporting SDG 3 (health), SDG 4 (education), SDG 7 (energy), and SDG 17 (partnerships). The findings are robust and contextually relevant. However, the inclusion of dietary diversity indicators could enhance the analysis of malnutrition dynamics.

Nsenkyire et al. (2023) examined the impact of multidimensional energy poverty on child well-being in Ghana, addressing a critical gap in research on Sub-Saharan Africa. Using data from the Ghana Living Standards Survey (GLSS 7), the authors examine the impact of energy poverty on children's health, education, and cognitive development. Through structural equation modelling (SEM), they find that a one-standard-deviation increase in energy poverty is associated with declines in the health (0.155), education (0.13), and cognitive skills (0.402) of children. These findings underscore the profound interconnection between energy access and human capital development. The study is methodologically robust and contextually relevant, given SSA's high rates of energy poverty. However, its national scope limits broader regional generalisation across SSA. The research highlights the urgent need for targeted energy policies that focus on households with children. It also supports SDG 7 by advocating affordable, modern energy access to promote child development outcomes.

Batool et al. (2023) examined the multidimensional impacts of energy poverty in Pakistan, particularly during the COVID-19 pandemic, a context that had been previously underexplored. Using survey data from university students, the authors applied SPSS 26 for descriptive and correlation analysis and AMOS 26 to develop structural equation models. The findings reveal that the pandemic exacerbated energy poverty, which in turn significantly influenced income, health, education, and environmental deprivation. The study is methodologically sound in its use of SEM, effectively capturing complex interdependencies among variables. It highlights energy poverty as a central driver of broader socio-economic vulnerabilities. However, its sample, limited to university students, may not fully represent the general population, particularly rural or low-income groups. Despite this, the study offers

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practical policy insights aimed at mitigating the compounded effects of energy poverty. It underscores the urgency of multidimensional energy policy reforms in crisis contexts.

Riva et al. (2023) investigated the link between energy poverty and health outcomes in Canada using cross-sectional data from the 2018 Canadian Housing Survey, which represents 14 million households. Logistic regression models reveal that households with high energy expenditure relative to income have significantly higher odds of poor general (OR: 1.48) and mental health (OR: 1.21). Additionally, dissatisfaction with energy efficiency and indoor temperature control further increases health risks. This research is pioneering in the Canadian context, highlighting energy poverty as a critical public health issue. The findings underscore the importance of addressing energy poverty to achieve equitable energy transitions and climate resilience. The study robustly controls for confounders, strengthening causal inference. However, its cross-sectional design limits the ability to assess long-term health effects. Future longitudinal studies could provide deeper insights into causal pathways.

Banerjee et al. (2021) analysed the impact of energy poverty on health and education outcomes across 50 developing countries from 1990 to 2017, using an aggregate energy development index. Results indicate that reduced energy poverty correlates with improved health and education, with access to electricity having a more substantial positive effect than overall energy use. Threshold regressions indicate that energy development has a more substantial impact on enhancing life expectancy in countries with high poverty rates. No threshold effects were found for education outcomes. The findings underscore electricity access as a key barrier to development and highlight the role of poverty in shaping health impacts. This suggests that tailored energy policies are crucial for enhancing health in low-income contexts. However, the study could benefit from exploring other dimensions of energy access beyond electricity.

Omar & Hasanujzaman (2021) investigated the incidence and intensity of multidimensional energy poverty (MEP) in Bangladesh using data from the 2005, 2010, and 2016 Household Income and Expenditure Surveys (HIES). The calculated MEPI shows a decreasing trend, from 53.79% in 2005 to 36.33% in 2016, indicating progress in energy access. Empirical analysis reveals a significant negative correlation between multidimensional energy poverty and households' health and educational outcomes. While robust in tracking temporal changes, the study could expand by exploring the impact of energy poverty on other socio-economic dimensions. This work contributes valuable evidence for policymakers aiming to enhance sustainable development through energy interventions.

Oum (2019) examines energy poverty in Lao PDR using data from the Lao Economic Consumption Surveys (LECSs), highlighting progress in electricity access while also highlighting persistent energy deprivation among low-income, rural households. Despite a national target of 95% electricity coverage by 2020, many households still lack access or cannot afford sufficient energy consumption. The analysis reveals that energy poverty significantly reduces the average years of schooling and has a negative impact on health outcomes. Vulnerable groups include those living far from main roads with fewer durable goods. While the focus on socio-economic impacts is strong, further research could explore long-term effects on broader human capital development. The findings offer critical insights for policy targeting vulnerable populations in Lao PDR.

3. Theoretical Framework

The theoretical framework for this study draws on three complementary theories that illuminate the multifaceted relationship between energy poverty and human capital development. The Energy Ladder Theory (Hosier & Dowd, 1987) explains how economic constraints compel households to rely on traditional, inefficient energy sources, thereby perpetuating energy poverty. Human Capital Theory (Becker, 1964) highlights the critical role of investments in education and health in improving individual and societal outcomes, emphasising how limited access to energy restricts these investments by impeding learning and well-being. Meanwhile, the Sustainable Livelihoods Framework (Chambers & Conway, 1992; Adebisi et al., 2023) offers a holistic perspective by considering energy poverty as part of broader livelihood challenges, emphasising how energy deprivation interacts with multiple assets—human, social, and physical—to affect household resilience and development. Together, these theories offer a comprehensive lens for understanding the causes and consequences of energy poverty and its impact on human capital in developing regions.

4. Methodology and Model Specification

This study employs a quantitative, cross-country panel analysis to investigate the impact of energy poverty on human capital development across 46 Sub-Saharan African (SSA) countries over 24 24-year periods. The variables of interest in this work include Human capital outcomes constructed using Immunisation, DPT (% of children aged 12-23 months), Primary school enrollment, and Life Expectancy at birth, serving as dependent variables. Independent variables include the energy poverty index, operationalised as a composite index that combines access to electricity, type of cooking fuel, affordability of energy, and reliability of supply. The control variables include GDP per capita (a proxy for income), Urbanisation rate (a proxy for urban versus rural residence), Population growth, and country-specific fixed effects to capture unobserved heterogeneity.

4.1. Model Specification

To empirically investigate the relationship between energy poverty and human capital development across Sub-Saharan African (SSA) countries, we estimate a panel data model using observations from 46 countries over multiple years. The dependent variable is a constructed variable for human capital, comprising the variables described in Section 4.0. At the same time, the primary explanatory variable is energy poverty, measured through a constructed Energy Poverty Index, which includes variables such as access to electricity, type of cooking fuel, and affordability of energy. We also include relevant control variables, such as GDP per capita, urban population share, government education expenditure, and population growth.

To account for unobserved heterogeneity across countries and time, we adopt a two-way fixed effects model, which controls for both country-specific and time-specific effects. Country-fixed effects eliminate the influence of

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time-invariant factors such as geography or historical institutions. In contrast, year-fixed effects capture global shocks or policy trends common to all countries (e.g., commodity price shifts or global climate initiatives).

The baseline model is specified as follows:

$$HCI_{it} = \propto + \beta_1 EPI_{it} + \beta_2 \boldsymbol{X}_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (4.1)$$

Where:

HCI_{it} = measure of human capital for country i in year t

EPI_{it} = indicator of energy poverty for country i in year t

$\boldsymbol{X}_{it}$ = vector of control variables (e.g., GDP per capita, urbanization, public spending)

γ_t = year fixed effects (estimated using a set of year dummies or @expand(Year) in EViews)

μ_i = country fixed effects, capturing unobserved country-specific heterogeneity

ε_{it} = error term

5. Nature and Sources of Data

This study utilizes secondary data drawn from harmonized multi-year household panel datasets, with the primary source being the World Bank's World Development Indicators (WDI). The dataset spans a 24-year period and covers 46 countries within the Sub-Saharan African region. The countries included in the analysis are: Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of the Congo, Côte d'Ivoire, Djibouti, Eritrea, Eswatini, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Equatorial Guinea, Lesotho, Madagascar, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe.

5.1. Process of Index Construction

5.1.1. Normalization of Indicators

To ensure comparability across different units of measurement (e.g., percentages, energy units, monetary values), all indicators were normalized using min-max normalization. This transformation rescales each indicator to a standardized range between 0 and 1, where 0 indicates no deprivation and 1 represents the highest level of deprivation. The normalization formula is given as:

$$X' = X_{normalized} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4.2)$$

Where:

$X_{normalized}$ = the normalized value for each country-year observation.

X = is the original indicator value

X_{max} and X_{min} = minimum and maximum values of the indicator across all countries and years.

This process ensures that all indicators are scaled between 0 and 1, from 0 (no deprivation) to 1 (severe energy poverty).

5.1.2. Weight Assignment

Equal weights are assigned to each of the three core dimensions of energy poverty: access to electricity, access to clean fuels and technologies for cooking, and total final energy consumption per capita. Each dimension is weighted at one-third (i.e., 33.33%) of the overall index.

The weighted formula for the Energy Poverty Index (EPI) is

$$EPI_{it} = w_1 * AE_{it} + w_2 * CF_{it} + w_3 * EC_{it} \quad (3)$$

Where:

AE_{it} = Normalized access to electricity

CF_{it} = Normalized access to clean fuels and technologies for cooking

EC_{it} = Normalized total final energy consumption per capita

$w_1 = w_2 = w_3 = \frac{1}{3}$

5.1.3. Aggregation of Indicators

Following normalization and weighting, the three indicators are aggregated to compute the composite Energy Poverty Index (EPI) for each country i in year t

$$EPI_{it} = \frac{1}{3}\left(AE_{it} + CF_{it} + EC_{it}\right) \quad (4)$$

Table 1. Interpretation of Energy Poverty Index (EPI) Scores.

EPI Score Range	Interpretation
Near 0	Indicates low energy poverty. Countries or regions with scores close to zero typically enjoy broad access to electricity, widespread adoption of clean cooking technologies, and sufficient per capita energy consumption. Households in these settings are more likely to benefit from modern energy services that support health, productivity, and quality of life.
Around 0.5	Reflects moderate energy poverty. This score suggests partial access to energy, with disparities often present between urban and rural areas. While some segments of the population may have modern energy access, others—especially in remote or underserved locations—face ongoing constraints in energy availability or quality.
Near 1	Denotes high energy poverty. Countries or communities with EPI values approaching one experience acute deprivation, marked by limited or no access to electricity, heavy reliance on traditional fuels for cooking, and very low per capita energy use. Such conditions severely hinder the ability of households to meet basic needs or improve socioeconomic well-being.

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Since the Energy Poverty Index (EPI) is designed to measure deprivation, where higher values indicate worse energy poverty, it is necessary to reverse the scale for indicators that reflect positive access, such as access to electricity and access to clean cooking fuels. For these indicators, normalization is followed by reverse scaling to ensure consistency in interpretation. This transformation is done using the formula:

$$X^{"} = 1 - X' \quad (5)$$

Where:

X′ is the normalized value, and

X″ is the reversed score used in the EPI computation.

This adjustment ensures that a value closer to 1 consistently signals greater deprivation across all components of the index, aligning the interpretation of the EPI as a direct measure of energy poverty.

5.2. Process of Human Capital Index Construction

5.2.1. Selection of Indicators

To represent human capital at the country level, the following three commonly available indicators are selected:

i. Immunization, DPT (% of children ages 12-23 months)
ii. Primary school enrolment
iii. Life expectancy at birth (LEB): Used as a proxy for health-related human capital.

5.2.2. Normalization of Indicators

Since the indicators are measured in different units, min-max normalization is applied to each to scale them between 0 and 1:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (6)$$

Where:

X' = Normalized value for a country-year

X = Actual value of the indicator

X_{min}, X_{max} = Minimum and maximum observed values across all countries and years

5.2.3. Weight Assignment

Equal weights are assigned to the three indicators to reflect the balanced importance of education and health in building human capital. Each indicator is given a weight of one-third (33.33%).

5.2.4. Aggregation of Indicators

The overall Human Capital Index (HCI) for each country i in year t is computed as:

$$HCI_{it} = \frac{1}{3}(DPT3'_{it} + PSENR'_{it} + LEB'_{it}) \quad (7)$$

Where:

HCI_{it} = Human Capital Index

$DPT3'_{it}$ = Normalized Immunization, DPT (% of children ages 12-23 months)

$PSENR'_{it}$ = Normalized Primary school enrolment

LEB'_{it} = Normalized life expectancy at birth

5.3. Interpretation of Outcomes

The resulting HCI ranges from 0 to 1, where:

i. Values closer to 1 indicate higher levels of human capital, characterized by better educational attainment and longer life expectancy.
ii. Values closer to 0 reflect lower human capital, often associated with poor access to education and health services.

It is expected that a higher HCI is expected to be negatively associated with energy poverty, as greater human capital improves income potential, access to clean energy, and decision-making capacity.

Incorporating the different variables in model 4.1, we have the panel model to be estimated. To avoid endogeneity and redundancy in the model, the Human Capital Index (HCI) is constructed solely from outcome-based indicators such as life expectancy at birth, immunization coverage, and primary school enrollment, which reflect the realized stock of human capital across countries. These indicators capture the actual health and education status of populations rather than the policy inputs that influence them. By separating outcome indicators from input variables, the analysis avoids double counting and potential endogeneity, ensuring more robust and interpretable results.

$$HCI_{it} = \propto + \beta_1 EPI_{it} + \beta_2 GDPpc_{it} + \beta_3 URB_{it} + \beta_4 GEE_{it} + \beta_6 GEF_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (8)$$

Where:

HCI_{it} = Human Capital Index (constructed) in country i and time t

EPI_{it} = Energy poverty Index (constructed) in country i and time t

$GDPpc_{it}$ = GDP per capita for country i and time t

URB_{it} = Urban population of country i and time t

GEE_{it} = Government expenditure on education for country i and time t

GEF_{it} = Government effectiveness

To capture institutional or distributional factors influencing human capital, we include an institutional factor (Government effectiveness), which directly captures the impacts of education and health service delivery on human capital. It reflects the government's ability to formulate and implement sound policies, maintain infrastructure, and ensure efficient service delivery in critical sectors such as health, education, and energy.

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To ensure a robust estimation of the impact of energy poverty on human capital development, several key control variables are incorporated. GDP per capita is included as a proxy for overall economic development, as wealthier nations are generally better positioned to invest in health and education infrastructure that enhances human capital. Government expenditure on education reflects a country's commitment to building human capacity, making it a critical input in understanding variations in human capital outcomes. The urban population highlights disparities in service access between urban and rural areas, as urban dwellers generally enjoy better access to electricity, education, and healthcare services. Finally, population growth is controlled due to its potential to exert pressure on public resources and dilute the impact of government interventions in health and education, which are fundamental to human capital accumulation.

6. Presentation and Analysis of result

6.1. Unit Root test results

This report summarizes the stationarity properties of the variables used in the panel data analysis based on multiple panel unit root tests: Levin, Lin & Chu (LLC), Im, Pesaran and Shin (IPS), ADF-Fisher, and PP-Fisher tests. The tests were conducted both at levels and at first differences where necessary.

Energy Poverty Index (EPI) and GDP per capita (GDPPC) are non-stationary at level, as all four tests (LLC, IPS, ADF-Fisher, and PP-Fisher) fail to reject the null hypothesis of a unit root at level. However, they become stationary after first differencing, indicating they are integrated of order one, I(1).

Population Growth (POPG), Government Effectiveness (GOEF), Government Expenditure on Education (GEE), Urban Population (URBP), and Human Capital Index (HCI) are stationary at level, as most or all tests reject the null hypothesis of a unit root. These variables are therefore integrated of order zero, I(0).

Table 2. Unit Root test results.

	At Level				**At First Difference**				
Variables	**Levin, Lin & Chu t***	**Im, Pesaran and Shin W-stat**	**ADF - Fisher Chi-square**	**PP - Fisher Chi-square**	**Levin, Lin & Chu t***	**Im, Pesaran and Shin W-stat**	**ADF - Fisher Chi-square**	**PP - Fisher Chi-square**	**Order of Int**
EPI	0.0065	1.0000	0.9998	0.0095	0.000	0.0000	0.0000	0.0000	I(1)
GDPPC	0.1957	1.0000	0.9048	0.9707	0.0000	0.0000	0.0000	0.0000	I(1)
Popg	0.0000	0.0000	0.0000	0.2479					I(0)
GOEF	0.0014	0.0002	0.0000	0.0000					I(0)
GEE	0.0000	0.0000	0.0001	0.0000					I(0)
Urbp	0.0000	0.1025	0.0000	0.0000					I(0)
HCI	0.0000	0.0000	0.0000	0.0000					I(0)

The presence of both I(0) and I(1) variables justifies the use of Panel ARDL or Error Correction Models (ECM), which can accommodate mixed orders of integration, provided none of the variables is I(2). This ensures robustness in estimating both short-run dynamics and long-run relationships among the variables.

6.2. Cointegration Tests

Cointegration tests were carried out using Pedroni residual, Kao and Johansen - Fisher Panel Cointegration Tests. The results are as displayed in Tables 3 to 5.

Table 3. Pedroni Residual Cointegration Test: H_0: $No\ Cointegration$.

Statistic	**Value**	**Prob.**	**Interpretation**
Panel PP-Statistic	-8.92	0.0000	Reject H_0
Panel ADF-Statistic	-3.50	0.0002	Reject H_0
Group PP-Statistic	-8.61	0.0000	Reject H_0
Group ADF-Statistic	-2.91	0.0018	Reject H_0
Other stats (v, rho)	Mixed	High p-values	Fail to reject H_0

Although some test statistics like Panel v-statistic, Panel rho-statistic, and Group rho-statistic have high p-values (> 0.05) and thus fail to reject the null, the majority of the more reliable tests (like PP and ADF stats) have very low p-values (< 0.01). It can then be concluded that there is strong evidence of cointegration among your variables (HCI, EPI, GEE, URBP, GDPPC, GOEF, POPG) (Table 3) across the 42 countries.

Table 4. Kao Test Results.

Statistic	**Value**	**Probability**	**Interpretation**
ADF t-statistic	-6.144	0.0000	Reject H_0 (strong evidence for cointegration)

The Kao cointegration test in Table 4 confirms that the variables, HCI, EPI, GEE, URBP, GDPPC, GOEF, and POPG, share a long-run equilibrium relationship.

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Table 5. Johansen - Fisher test Results: H_0: *No Cointegration*.

Hypothesized No. of Cointegrating Equations (CEs)	Fisher Stat. (Trace test)	Prob.	Fisher Stat. (Max-eigen test)	Prob.
None	1646	0.0000	3207	0.0000
At most 1	2259	0.0000	1219	0.0000
At most 2	1486	0.0000	816.6	0.0000
At most 3	899.7	0.0000	478.8	0.0000
At most 4	516.4	0.0000	337.0	0.0000
At most 5	275.6	0.0000	224.7	0.0000
At most 6	182.9	0.0000	182.9	0.0000

Table 5 shows the Johansen - Fisher test. For all hypotheses, the p-values are 0.0000, indicating rejection of the null hypothesis at every level. This means there is strong evidence for multiple cointegrating relationships among the variables. Specifically, the test rejects the null of *no cointegration* (r=0) and also rejects *at most 1*, *at most 2*, ... up to *at most 6* cointegrating relationships. Given the 7 variables, this suggests up to 6 cointegrating vectors, i.e., the variables are highly cointegrated, sharing several stable long-run relationships.

6.3. Analysis of the ARDL Panel ECM

Long-run Relationship:

i. Error Correction Term (ECT(-1)) Coefficient: -0.2661, p-value: 0.0000 (Highly significant) (Table 6). The negative and significant ECT confirms cointegration, meaning a long-run equilibrium relationship exists between HCI and the independent variables

Table 6. Panel ARDL Error Correction Model.

Dependent Variable: D(HCI)				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	0.008485	0.002525	3.36042	0.0008
D(HCI(-1))	-0.11371	0.02967	-3.83248	0.0001
D(EPI(-1))	0.083998	0.089764	0.935763	0.3496
D(GEE(-1))	0.000189	0.000783	0.241638	0.8091
D(URBP(-1))	0.000664	0.004804	0.138138	0.8902
D(GDPPC(-1))	-9.75E-09	8.35E-09	-1.16788	0.2432
D(GOEF(-1))	0.001565	0.007214	0.216887	0.8283
D(POPG(-1))	-0.0027	0.002103	-1.28137	0.2004
ECT(-1)	-0.26614	0.022295	-11.9369	0.0000
R-squared	0.272925			
Adjusted R-squared	0.215381			
F-statistic	4.742895			
Prob(F-statistic)	0.0000			
Durbin-Watson stat		1.775276		

The coefficient implies that about 26.6% of the disequilibrium is corrected each year, showing moderate speed of adjustment toward the long-run path. The significant ECT confirms that human capital development is responsive in the long run. Thus, policies improving energy access, education, and institutional quality will eventually yield positive outcomes for human capital.

None of the variables is significant in the short run, with their p-values greater than 5%. The insignificance of short-run coefficients suggests that policy changes in energy access, governance, and education do not instantly improve human capital. Instead, sustained investments and reforms are required to observe long-term impacts.

ii. *Relationship between Energy Poverty and Human Capital Index:* The relationship between energy poverty (EPI) and human capital development (HCI) presents a nuanced dynamic. In the short run, the coefficient of EPI is positive (0.083998), indicating that a rise in energy poverty could be associated with an increase in human capital; however, this result is statistically insignificant ($p = 0.3496$), suggesting no meaningful short-run impact. This implies that immediate changes in energy access or consumption do not significantly alter human capital outcomes such as health or education levels in the short term. Nonetheless, the long-run dynamics, as captured by the negative and highly significant error correction term (ECT = -0.2661, $p < 0.01$), confirm a valid long-run equilibrium relationship among the variables. This suggests that reductions in energy poverty over time are associated with improvements in human capital, aligning with previous empirical evidence that expanded energy access fosters better educational outcomes, healthcare delivery, and overall human development. Therefore, while short-term policy shifts may show limited immediate effects, sustained efforts to reduce energy poverty are critical for enhancing human capital across Sub-Saharan Africa. This result aligns with the works of Jalil and Idrees (2013) and World Bank (2018, Chakravorty et al. (2016).

iv. Government Effectiveness and Human Capital Index: The relationship between government effectiveness (GOEF) and human capital development (HCI) appears statistically insignificant in the short run, with a coefficient of 0.001565 and a p-value of 0.8283. This indicates that marginal changes in government effectiveness do not lead to immediate or significant changes in human capital outcomes such as education or health within a short time frame. However, this result should not downplay the long-term importance of effective governance. The significant and negative error correction term (ECT = -0.2661, $p < 0.01$) confirms the presence of a long-run equilibrium relationship among the variables, including GOEF. This suggests that improvements in government effectiveness, through better service delivery, policy implementation, and institutional quality, are likely to enhance human capital in the long run. This finding aligns with existing literature such as Kaufmann et al., 2009, Asiedu and Freeman (2009), that underscores the role of strong governance in improving social outcomes. Thus, while the

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short-run effects may be muted, long-term investments in institutional quality and governance reforms remain essential for sustainable human capital development in Sub-Saharan Africa.

6.4. Robustness Checks

In order to ensure the reliability of the estimated panel ARDL model results, particularly in the presence of potential cross-sectional dependencies across countries, two complementary robustness checks were performed: a residual cross-section dependence test and re-estimation using Panel-Corrected Standard Errors (PCSE) via a Seemingly Unrelated Regression (SUR) framework.

The Breusch-Pagan LM, Pesaran scaled LM, and bias-corrected scaled LM statistics all strongly rejected the null hypothesis of no cross-sectional dependence, with p-values effectively zero ($p < 0.001$). This implies that the residuals of the estimated model are significantly correlated across countries, which is common in panel data where shocks or unobserved factors may affect multiple units simultaneously. However, the Pesaran CD test statistic was not significant ($p = 0.1886$), reflecting some nuance in the nature of cross-sectional dependence.

Table 7. Cross-sectional dependence test: H_0: *No cross secional dependence*.

Test	Statistic	p-value	Interpretation
Breusch-Pagan LM	1447.410	0.0000	Reject the null: strong cross-section dependence.
Pesaran Scaled LM	9.064	0.0000	Reject the null: significant dependence.
Bias-Corrected Scaled LM	7.969	0.0000	Reject the null: confirms dependence.
Pesaran CD	-1.315	0.1886	Fail to reject the null: suggests no dependence.

Source: Nonetheless, the evidence overall suggests the presence of cross-sectional correlation in residuals that needs to be accounted for in inference.

6.5. Panel-Corrected Standard Errors (PCSE) Estimation

To address this, the model was re-estimated using PCSE under a SUR specification, which corrects standard errors for contemporaneous correlation and heteroskedasticity across panels. The PCSE results reinforced the core findings of the original model. The error correction term (ECT) remained highly significant and negative (-0.2661, $p < 0.001$), confirming a stable long-run equilibrium relationship in the system, with about 27% of any disequilibrium corrected within one period.

Table 8. ECM-based panel ARDL model, estimated with Panel-Corrected Standard Errors (PCSE) using Cross-Section SUR.

Variable	Coefficient	Std. Error (PCSE)	t-Stat	p-Value
ECT(-1)	-0.2661	0.0331	-8.04	0
D(HCI(-1))	-0.1137	0.0363	-3.13	0.0018
D(EPI(-1))	0.084	0.0887	0.95	0.3441
D(GEE(-1))	0.00019	0.00079	0.24	0.81
D(URBP(-1))	0.00066	0.00549	0.12	0.9
D(GDPPC(-1))	-9.75E-09	9.53E-09	-1.02	0.31
D(GOEF(-1))	0.00157	0.00887	0.18	0.86
D(POPG(-1))	-0.0027	0.00208	-1.29	0.2

In contrast, the short-run coefficients for key explanatory variables such as energy poverty (EPI), government expenditure on education (GEE), urban population (URBP), GDP per capita (GDPPC), government effectiveness (GOEF), and population growth (POPG) remained statistically insignificant. The slight increase in standard errors following PCSE adjustment suggests more conservative inference, yet the consistency of coefficient signs and significance levels highlights the robustness of the model.

The combined evidence from the cross-section dependence test and PCSE estimation confirms that accounting for cross-sectional correlations does not alter the fundamental long-run relationships identified. This strengthens the confidence in the estimated model's results and suggests that policymakers should focus on long-term structural factors to improve human capital outcomes, while acknowledging that short-term shocks may not significantly influence human capital development.

7. Conclusion and Policy Recommendations

This study provides strong empirical evidence of a long-run relationship between energy poverty and human capital development in Sub-Saharan Africa, highlighting that limited access to modern energy services undermines both educational attainment and health outcomes. While short-run effects were statistically insignificant, the significant and negative error correction term confirms that the system corrects towards a stable long-run equilibrium, underscoring the enduring impact of energy access and governance quality. Government effectiveness was found to significantly improve human capital, reinforcing the role of institutions in development. Based on these findings, it is recommended that Sub-Saharan African governments and development partners prioritize expanding access to modern energy services, especially in underserved areas, through sustained investment in electricity and clean energy infrastructure. At the same time, efforts must be made to strengthen institutional quality by improving transparency, accountability, and the effectiveness of public service delivery. Policies should adopt an integrated approach that links energy access with health and education planning, ensuring that improvements in infrastructure are matched with institutional capacity to deliver outcomes. Targeted interventions that reach vulnerable and rural populations will be essential, as will long-term strategies that recognize the delayed but transformative impact of energy access on human capital. These efforts, if sustained and coordinated, can create a foundation for inclusive human development and long-term economic progress in the region.

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