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Human Capital Development amid Energy Injustice: Rethinking Energy Justice and Institutional Quality in Sub-Saharan Africa

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ABSTRACT

This study examines the nexus between energy justice, institutional quality, and human capital development (HCI) in Sub-Saharan Africa, using a balanced panel of 46 countries between 2000 and 2023. Employing System GMM and validating with a Panel ARDL-ECM, the results reveal that energy justice significantly enhances human capital outcomes by improving access, affordability, and equity in energy services. Institutional quality also emerges as a critical enabler of HCI through improved governance and resource management. Interestingly, the interaction between energy justice and institutional quality is negative and significant, suggesting diminishing marginal returns when both improve simultaneously. The strong and significant error correction term confirms long-run convergence, reinforcing the robustness of the results. Policy recommendations emphasize integrated strategies that combine governance reforms with equitable energy policies to maximize human capital development in the region. The findings provide fresh insights into the structural pathways linking energy governance and inclusive development.

INTRODUCTION

Sub-Saharan Africa (SSA) remains the global epicenter of energy poverty. According to the International Energy Agency (IEA, 2024), nearly 600 million people in the region still lack electricity, representing about 75% of the world's unelectrified population. In addition, over 970 million people, that is, four out of five globally without access to clean cooking, continue to rely on biomass such as wood, charcoal, and kerosene (IEA, 2024; World Bank, 2023). These deficits impose severe human development penalties: limited lighting and ICT access constrain education, reliance on polluting fuels drives respiratory illnesses and premature mortality, and unreliable energy supply undermines enterprise productivity and health service delivery (Grimm *et al.,* 2017).

Beyond the question of access, the quality and affordability of energy services in SSA remain critically low. Firms report an average of 8.7 outages per month, with power disruptions reducing sales by up to 10% annually in countries such as Nigeria and Tanzania (World Bank, 2020). For households, unreliable supply compromises children's study time and digital learning, while regressive tariff structures and misallocated subsidies disproportionately burden the poor (Blimpo & Cosgrove-Davies, 2019). This situation reflects a broader condition of energy injustice: wealthier and urban households benefit from higher-quality and more affordable electricity, while rural, poor, and marginalized groups remain trapped in costly and unsafe energy arrangements.

Institutional quality plays a decisive role in shaping these patterns. Evidence suggests that electricity allocation is often politicized, particularly around elections (Min, 2015), while rent-seeking behaviour and regulatory capture undermine utilities' capacity to deliver reliable service (Eberhard *et al.,* 2016). Conversely, countries with stronger governance, such as Ghana and Kenya have demonstrated greater progress in off-grid solar and mini-grid deployment, while fragile and rent-seeking contexts like South Sudan and Nigeria continue to underperform despite abundant resources (Lee *et al.,* 2020). These dynamics highlight that energy access alone does not automatically translate into human capital gains; the institutional context mediates these outcomes.

Human capital, understood as the stock of knowledge, skills, and health embodied in people, remains the cornerstone of sustainable development. Yet SSA continues to underperform, with the 2023 UNDP Human Development Index showing that 33 of the 36 countries in the "Low Human Development" category are located in the region (UNDP, 2023). Growing attention now focuses on the structural role of energy poverty and, more specifically, energy injustice in constraining the accumulation of human capital across SSA. Energy injustice in the region is multidimensional: distributional inequities persist, with rural access rates below 30% compared to urban averages of 78% (IEA, 2024); procedural inequities limit community participation in tariff setting or subsidy design (Aklin *et al.,* 2018); and recognition inequities neglect the needs of vulnerable groups, such as women exposed to household air pollution, which causes an estimated 700,000 premature deaths annually (WHO, 2023).

Despite these insights, three major research gaps remain.

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First, existing studies emphasize electrification rates but underexplore how qualitative dimensions of energy, reliability, affordability, safety, and capacity shape human capital outcomes in SSA (Grimm *et al.,* 2017; Blimpo & Cosgrove-Davies, 2019). Second, the role of institutional quality in moderating the relationship between energy access and human capital remains insufficiently examined, risking policies that over-prioritize infrastructure while neglecting governance reform. Third, although the literature on energy justice highlights distributional, procedural, and recognition dimensions, these mechanisms are rarely operationalized in quantitative models, leaving the specific channels through which energy injustice erodes human capital largely untested in SSA contexts.

This study addresses these gaps by employing a quantitative panel-data methodology that integrates cross-country datasets on energy access and quality (World Bank, IEA, SE4ALL), institutional governance (Worldwide Governance Indicators), and human capital (World Bank Human Capital Index, Barro-Lee educational attainment, WHO health outcomes). Using advanced econometric techniques, including Panel System GMM and moderation/interaction effects analysis, the research will quantify the effects of qualitative energy dimensions, identify the role of institutional quality, and empirically test the mechanisms of energy injustice. In doing so, the study moves beyond descriptive statistics to provide evidence-based insights on how energy access and governance jointly shape human capital development in SSA, with implications for both theory and policy.

This study is organized into five main sections. The second section reviews the relevant literature, combining both theoretical perspectives and empirical findings. The third section details the research methodology, including the model specification, data sources, and variable measurement. Section four presents the empirical results alongside their interpretation and analysis. Finally, section five concludes the study and provides policy recommendations derived from the findings.

LITERATURE REVIEW

Empirical Literature Review

Akyuz (2025) highlights the gendered dimensions of coal-related environmental hazards in Istanbul's Mustafa Kemal Neighborhood, showing through 44 semi-structured interviews that coal use creates distributive injustice disproportionately affecting women, with patriarchal norms, poverty, and religious values intensifying vulnerability. Policy measures proposed include halting free coal distribution, expanding women's workforce participation, and mainstreaming gender perspectives in energy policies. However, the study's localized scope limits the generalizability of its findings beyond Turkey. Similarly, Woods *et al.* (2024) explores how energy-efficiency policies in Norway, despite abundant hydropower, aggravate energy poverty among low-income households. Interviews across three cities reveal that efficiency investments deepen inequality, especially where social housing policies are disconnected from energy reforms. Caring practices help families cope but mask deeper structural injustices, underscoring the need to integrate care into energy justice discourses. Yet, the study relies heavily on qualitative insights, offering limited quantifiable evidence of policy impacts. At the global scale, Mose (2024) conceptualizes the just energy transition as a justice-oriented restructuring of energy systems, framing energy access as a legal right. Emphasizing distributive, procedural, recognition, cosmopolitan, and restorative justice, the study calls for embedding energy justice within international frameworks and domestic law to guarantee equitable delivery of SDG 7. Still, while theoretically innovative, it lacks empirical validation to assess practical outcomes of these tenets.

Habersbrunner *et al.* (2024) explored the origins, organization, and role of energy communities (ECs) in Europe, Turkey, and Uganda, applying gender dimensions such as decision-making, resources, and health to assess equity. Findings revealed that women's participation remains limited, with case studies showing both progress and persistent gender gaps. The study urged mainstreaming gender in energy policies, arguing that gender-sensitive ECs can transform energy systems, though it relied only on secondary sources. García *et al.* (2024) investigated the socio-ecological impacts of hydroelectric dams in the Brazilian Amazon, showing that many households still depend on diesel despite nearby dams, while spatial and political injustices worsened access and raised prices. This demonstrates how dams may deepen local inequalities, though the focus is context-specific. Sreekanth (2024) examined the global energy transition, emphasizing renewable deployment, policy innovation, and holistic sustainability strategies, but lacked empirical demonstration of policy success. Trakic *et al.* (2024) linked energy justice to human rights, climate justice, and social equity, highlighting regulations, incentives, and inclusive values as crucial, though the framework remained largely conceptual. Collectively, these works illustrate diverse pathways to just and sustainable energy transitions but underscore persistent gaps between theory and practice.

Castán (2024) underscores the persistent role of gender in shaping energy provision and access, particularly within community energy and sustainable transitions, showing how gender relations reinforce structural inequalities and restrict women and gender non-conforming groups in the green labour market. Drawing on feminist and intersectional theory, the work reframes energy justice as deeply embedded in social power relations, though its insights remain conceptual with limited empirical grounding. Castro-Diaz *et al.* (2024), through a multitemporal case study of the Belo Monte dam in Brazil, highlights how affected fishers experienced diverse and shifting energy injustices across construction and operation phases, revealing the overlooked socio-environmental burdens of large-scale projects. The study illustrates the importance of multidimensional and dynamic approaches in analyzing community experiences of energy transition. Seera (2024) situates energy technology innovation within the broader framework of global energy injustices, identifying distributive, procedural, and recognition challenges that persist despite technological advances. While renewable energy, smart grids, and machine learning show potential for rural electrification and energy efficiency, ethical and implementation challenges risk reinforcing inequities without strong policy alignment. Finally, Maidin (2024) examines energy justice in ASEAN through the lens of human rights law, emphasizing equality in participation and the regional dilemma of reconciling international pressure for renewable adoption with domestic socio-economic constraints. Together, these works reveal that energy transitions are not only technological shifts but also deeply political, social, and justice-laden processes that demand inclusive, context-sensitive strategies.

Libertson (2024) underscores the risk of transferring existing social inequalities into low-carbon transitions, extending energy justice analysis from disadvantaged users to supply-side actors. Through 24 interviews with Swedish utilities, four archetypes, System Operator, Analyst, Flexibility Advocate, and Entrepreneur emerged, reflecting complementary yet misaligned views of justice in practice versus theory. Mulvaney (2024) highlights how global solar expansion reshapes socio-ecological relations, driving mineral demand, labor shifts, occupational risks, land-use conflicts, and sustainability issues like end-of-life disposal. Using the concept of embodied energy injustice, it stresses governance gaps across supply chains. Akrofi *et al.* (2024) review 26 African renewable projects, identifying distributive (58%), procedural (18%), restorative (15%), and recognition (9%) injustices, with consequences such as inequality (49%), resource dispossession (18%), and institutional lock-in (12%). Alford-Jones (2022) finds Guatemalan hydropower conflicts arise from weak justice protections, with communities successfully halting 65% of projects. Perez-Sindin *et al.* (2022) quantify spatial energy injustice in Spain, Denmark, and South Korea, revealing rural–urban divides and offering new indices to guide equitable policy.

Theoretical Framework

The theoretical foundation for examining human capital development in the age of energy injustice is anchored in Amartya Sen's Capability Approach (Sen, 1999), which emphasizes that development should be measured by people's ability to expand their freedoms and access opportunities, including equitable energy access that enhances education, health, and productivity. Complementing this is Sovacool and Dworkin's Energy Justice Framework (2014), which highlights distributive, procedural, and recognition justice in evaluating energy systems, stressing that energy projects often generate inequities that undermine social welfare. Finally, Douglas North's Institutional Theory (1990) underscores the role of formal and informal institutions in shaping economic performance, particularly how governance quality mediates access to and distribution of energy resources. Synthesizing these perspectives provides a multidimensional lens: Sen's capability approach highlights how energy access shapes human development, the energy justice framework exposes inequalities and injustices embedded in energy transitions, while institutional theory explains how governance structures can either mitigate or reinforce these inequities. Together, they show that sustainable human capital development in Sub-Saharan Africa requires not just technological solutions but also institutional reforms and justice-oriented policies that ensure inclusive and equitable energy access.

MATERIALS AND METHODS

This study employs a quantitative panel data approach to investigate the nexus between human capital development, energy injustice, and institutional quality in Sub-Saharan Africa. Panel data is suitable as it captures both temporal dynamics and country-specific heterogeneity. The empirical strategy is based on the System Generalized Method of Moments (System GMM) estimator of Arellano and Bover (1995) and Blundell and Bond (1998), which addresses endogeneity, unobserved heterogeneity, and dynamic effects in development studies.

The dependent variable, Human Capital Development (HCD), is proxied by a constructed Human Capital Index (HCI), since consistent World Bank HCI data are unavailable for all years and countries. Following standard index-construction methods, the HCI combines school enrollment (primary and secondary), life expectancy at birth, and immunization (DPT % of children 12–23 months), standardized through min–max normalization (Booysen, 2002; OECD, 2008), weighted, and aggregated into a composite index consistent with prior multidimensional development research (Noorbakhsh, 1998; Alkire & Foster, 2011; UNDP, 2010; Jolliffe & Prydz, 2016). The main explanatory variable, Energy Injustice (EINJ), captures inequalities in energy access and reliance. It is proxied by indicators such as electricity access, renewable energy share, rural–urban electrification gap, and Voice & Accountability and Regulatory Quality, drawn from World Bank WDI, IEA, and AfDB, and combined into a normalized composite index. Institutional Quality (INSTQ) is measured using the Worldwide Governance Indicators (WGI), aggregating six governance dimensions (control of corruption, government effectiveness, political stability, regulatory quality, rule of law, and voice and accountability) following Kaufmann *et al.* (2010). Control variables include GDP per capita (constant 2015 US$) for income, FDI inflows (% of GDP) for external financing, population growth as a demographic factor, and gross fixed capital formation (% of GDP) to proxy domestic investment.

Although energy injustice was initially framed as an Energy Injustice Index (EINJ), the computation ensures that higher values reflect lower injustice. Therefore, for consistency and ease of interpretation, the variable is henceforth referred to as the Energy Justice Index (ENJ)

Model specification

Baseline Model (Direct Effects)

Examining the impact of energy injustice (ENJ) and institutional quality (INSTQ) on human capital development (HCD), controlling for GDP per capita, FDI, population growth, and gross capital formation

$$HCD_{it} = \beta_0 + \beta_1 HCD_{it-1} + \beta_2 ENJ_{it} + \beta_3 INSTQ_{it} + \beta_4 \mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Interaction Model (Moderating Effects)

Testing whether institutional quality moderates the effect of energy injustice on human capital development.

$$HCD_{it} = \propto_0 + \alpha_1 HCD_{it-1} + \alpha_2 ENJ_{it} + \alpha_3 INSTQ_{it} + \alpha_3 (INSTQ_{it} \times ENJ_{it}) + \alpha_4 \mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where the variables are as defined in 3.0, Xit = Control variables, μi = Country specific effect, λt = Time specific effect, and εit = Error Term

Estimation Technique and Justification

This study adopts the System Generalized Method of Moments (System GMM) estimator (Arellano & Bover, 1995; Blundell & Bond, 1998), suitable for dynamic panel data with many countries and shorter time periods. System GMM is justified because it addresses endogeneity from reverse causality and omitted variables, controls for unobserved country-specific heterogeneity, and captures the dynamic nature of human capital development through lagged dependent variables. By relying on internal instruments, it also mitigates weak instrument bias, thus ensuring robust and consistent estimates for analysing the interplay between energy injustice, institutional quality, and human capital in Sub-Saharan Africa.

Robustness Strategy: Panel ARDL–ECM (PMG)

Since the variables are integrated of mixed order: I(0) and I(1), but none I(2), the Autoregressive Distributed Lag model estimator of Pesaran, Shin & Smith (1999) is ideal. It (i) models short-run dynamics plus long-run cointegration simultaneously, (ii) allows country-specific short-run coefficients and error-correction speeds, and (iii) imposes homogeneous long-run coefficients, well suited to SSA where adjustment speeds differ but long-run technology/institutional parameters can be comparable. The ARDL ECM is modelled as:

$$\Delta HDI_{i,t} = \quad \emptyset_i \left(HCD_{it-1} - \varphi_1 ENJ_{i,t-1} - \varphi_2 INSTQ_{i,t-1} - \varphi_3 INTA_{i,t-1} - \varphi_4 X_{i,t-1} \right) + \sum_{j=1}^{p-1} \gamma_{ij} \Delta HDI_{i,t-j} + \sum_{k=0}^{q1-1} \omega_{1ik} \Delta ENJ_{i,-t-k} + \sum_{k=0}^{q2-1} \omega_{2ik} \Delta INSTQ_{i,t-k} + \sum_{k=0}^{q3-1} \omega_{3ik} \Delta INTA_{i,t-k} + \sum_{k=0}^{q4-1} \omega_{4ik} \Delta \mathbf{X}_{i,t-k} + \tau_t + \epsilon_{it}$$

Where: φ(i)= are common across countries (long-run homogeneity), ω1ik, ω2ik, ω3ik, ω4ik = are country-specific (short-run heterogeneity), INTER = Interactive moderating term, Øi = Error Correction Term (which must be negative and significant).

Construction of Composite Indices

The study constructs three composite indicators: Human Capital Index (HCI), Energy Injustice Index (ENJ), and Institutional Quality Index (INSTQ), following the standard multi-dimensional index-building approach in the development literature (Booysen, 2002; Alkire & Foster, 2011; OECD, 2008). The procedure involves three main steps: (i) selection and justification of indicators under each pillar, (ii) normalization and orientation of indicators, and (iii) aggregation into a composite score.

Selection and Justification of Indicators

Human Capital (HCI): Proxied using primary school enrolment, life expectancy at birth, and immunization (DPT % of children 12–23 months), which jointly capture education and health dimensions of human capital (World Bank, 2018).

Energy Injustice (ENJ): Constructed from urban–rural electricity access gap (distributional equity), clean cooking access (%) (energy poverty), voice & accountability and regulatory quality (institutional/participation dimension). These reflect the pillars of distributive, procedural, and recognition justice in the energy justice framework (Sovacool *et al.,* 2017; Jenkins *et al.,* 2020).

Institutional Quality (INSTQ): Based on World Governance Indicators (control of corruption, government effectiveness, regulatory quality, rule of law, political stability, voice & accountability), widely used in institutional development literature (Kaufmann *et al.,* 2010).

Normalization and Orientation of Indicators

Indicators are placed on a uniform 0–1 scale using min-max normalization:

$$X_{ij}^{norm} = \frac{X_{ij} - min(X_j)}{max(X_j) - min(X_j)}$$

Note:

Positive-oriented indicators (higher values = better outcome, e.g., school enrolment, life expectancy, clean cooking access) retain the above form. Negative-oriented indicators (where higher values imply worse outcomes, e.g., urban–rural access gap) are inverted and

$$X_{ij}^{*} = 1 - X_{ij}^{norm},$$

Where: Xij^* is the inverted data. This ensures all variables are aligned such that higher values represent more favorable conditions (higher human capital, lower injustice, stronger institutions).

Aggregation into Composite Index

The normalized indicators are aggregated using an equal-weight arithmetic mean (following UNDP's HDI and similar composite indices):

$$Index_j = \frac{1}{n} \sum_{i=1}^{n} X_{ij}^{*}$$

Where: $Index_j$ is the composite score for dimension j

(HCI, ENJ, INSTQ), n is the number of indicators, and X_{ij}^{normis} the normalized (and if required, inverted) value.

Interpretation of Indices

Human Capital Index (HCI): Higher values imply stronger health–education outcomes.

Energy Justice Index (ENJ): Since inverted variables are applied, a higher score indicates lower injustice (greater fairness), while lower scores reflect persistent inequities in access, affordability, or participation.

Institutional Quality (INSTQ): Higher values indicate stronger governance and institutional performance.

Data and Sources

The study uses a panel dataset for Sub-Saharan African countries, combining both constructed and directly sourced variables. Human Capital Development is proxied by the Human Capital Index (HCI), while institutional quality is drawn from the Worldwide Governance Indicators (WGI). Energy injustice is measured through a composite index, with controls such as GDP per capita, FDI, population growth, and gross capital formation obtained from the World Bank's World Development Indicators (WDI). This mix of constructed and direct measures ensures comprehensive coverage of the study objectives (Table 1).

RESULTS AND DISCUSSION

This section presents and interprets the key findings from the empirical investigation, linking them to the study's

Table 1: Data variable, sources and measurement

Variable (short)	Role in model	Measurement / unit (annual)	Primary source(s)	Status (constructed / used for construction / direct)
HCI (composite)	Dependent	0–1 composite index (min–max normalized & weighted of components below)	Constructed from Barro-Lee, WDI, WHO/GBD, UNESCO UIS	Constructed (primary HCD proxy)
School enrollment (primary + secondary)	Component of HCI	Gross/net enrollment rate (%)	UNESCO UIS; WDI; Barro-Lee	Used for construction
Life expectancy at birth	Component of HCI	Years	WDI; WHO	Used for construction
Immunization	Component of HCI	(DPT % of children 12–23 months)	WDI; WHO	Used for construction
ENJ (Energy Injustice Index)	Main explanatory (energy injustice)	0–1 composite (z-score or min–max of pillars DI/PI/RI)	Constructed from DHS/LSMS, WDI/IEA, WGI, enterprise surveys	Constructed
Urban–rural access gap	Distributional pillar (DI)	Urban access % − Rural access %	DHS; LSMS; WDI; IEA	Used for construction
Voice & Accountability / Regulatory Quality (WGI)	Procedural pillar (PI proxy)	WGI score (−2.5 to 2.5) (reverse-coded for injustice)	Worldwide Governance Indicators (Kaufmann *et al.,* 2010)	Used for construction
Electricity access (%)	Distributional input	% population with access to electricity	WDI; IEA; SE4ALL	Used for construction
Clean cooking access (%)	Distributional input	% population with clean cooking fuels	WDI; IEA; WHO	Used for construction
INSTQ (Institutional quality)	Moderator / Explanatory	Composite WGI mean (z-standardized) or IIAG score	WGI; Mo Ibrahim IIAG; V-Dem	Constructed composite)
GDP per capita (constant 2015 US$)	Control	GDP per capita, PPP or constant US$	WDI; Penn World Tables; IMF WEO	Direct
FDI inflows (% GDP)	Control	Net FDI inflows as % of GDP	WDI; UNCTAD	Direct
Population growth rate (%)	Control	Annual % growth	WDI	Direct

Gross capital formation (% GDP)	Control	GCF % GDP	WDI	Direct

Source: Author-generated

objectives and theoretical framework. The results are organized to highlight both short-run and long-run dynamics, while also examining interactive effects and transmission mechanisms where applicable. Emphasis is placed on the statistical significance, magnitude, and direction of relationships, as well as their alignment or divergence from existing literature. The analysis further explores regional variations and context-specific implications, providing nuanced insights into how institutional, economic, and environmental factors jointly shape sustainable and inclusive development outcomes.

Panel Unit Root test

Table 2 shows the results from Levin, Lin & Chu (LLC), Im, Pesaran & Shin (IPS), ADF-Fisher, and PP-Fisher panel unit root tests reveal a mixed order of integration among the variables. Stationary at Level [I(0)]: HCI, Popg, FDI, INSTQI, ENJ, LNGFCF, and the interaction term (ENJINSTQ) reject the null of a unit root across most tests, indicating stationarity at levels.

There is no I(2) variables: Since none of the series is integrated beyond order one, the dataset is suitable for dynamic panel approaches such as System GMM and also allows estimation with Pooled Mean Group (PMG) ARDL ECM, which requires a mix of I(0) and I(1). This implies that the System GMM approach remains appropriate for addressing potential endogeneity and dynamic relationships. Similarly, the presence of a mixed integration order (I(0) and I(1)) further justifies a PMG/ARDL-ECM robustness check to capture both short- and long-run dynamics.

Table 2: Panel 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**
HCI	0.0000	0.0000	0.0000	0.0000					I(0)
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)
FDI	0.0000	0.0000	0.0000	0.0000					I(0)
INSTQI	0.0000	0.001	0.0000	0.0000					I(0)
ENJ	0.0179	0.6729	0.0008	0.0019					I(0)
LNGFCF	0.0066	0.2750	0.0302	0.008					I(0)
ENJINSTQ	0.0000	0.0016	0.0000	0.0000					i(0)

Source: Author-generated

Panel Cointegration Test

The results (Table 3) from both the Kao Residual Cointegration Test and the Johansen Fisher Panel Cointegration Test provide strong evidence of a long-run equilibrium relationship among the study variables (HCI, ENJ, INSTQ, ENJINSTQ, FDI, GDPPC, LNGFCF, and POPG).

Table 3: Panel Cointegration Test Results

Test Type	**Statistic**	**Probability**	**Interpretation**
Kao Residual Cointegration Test	ADF t-stat = -6.296	0.0000	Reject null of no cointegration – evidence of cointegration
Johansen Fisher Panel Cointegration Test	Trace Test		
None	62.38	0.9883	Fail to reject → no cointegration at r=0
At most 1	33.27	1.0000	Fail to reject
At most 2	760.8	0.0000	Reject null – evidence of ≥ 3 cointegrating vectors
At most 3	1817.0	0.0000	Reject null

At most 4	1043.0	0.0000	Reject null
At most 5	553.7	0.0000	Reject null
At most 6	310.0	0.0000	Reject null
At most 7	218.1	0.0000	Reject null
Johansen Fisher Panel Cointegration Test	**Max-Eigen Test**		
None	62.38	0.9883	Fail to reject
At most 1	420.1	0.0000	Reject null – evidence of ≥ 2 cointegrating vectors
At most 2	760.8	0.0000	Reject null
At most 3	1141.0	0.0000	Reject null
At most 4	605.8	0.0000	Reject null
At most 5	351.8	0.0000	Reject null
At most 6	248.6	0.0000	Reject null
At most 7	218.1	0.0000	Reject null

Source: Author-generated

The Kao test rejects the null hypothesis of no cointegration at the 1% significance level (ADF = –6.296, $p < 0.01$), confirming that the variables are cointegrated.

The Johansen Fisher test further supports this finding. While the null hypothesis of no cointegration could not be rejected at $r = 0$, the results strongly reject the null from $r \geq 2$ onwards in both the Trace and Maximum Eigenvalue statistics ($p = 0.000$). This indicates the presence of multiple cointegrating vectors, suggesting stable long-run relationships among the variables.

Since cointegration is established, it is appropriate to proceed with models that capture both the short-run dynamics and long-run equilibrium, such as a Panel ARDL/ECM or System GMM with an error-correction specification. This ensures that any short-run deviations among the variables eventually converge to a stable long-run path.

Discussion of Results

Baseline Model

The baseline System GMM estimation (Table 4) investigates the determinants of human capital index (HCI) in Sub-Saharan Africa for the period 2000–2023. The model results reveal a strong dynamic persistence in human capital development, as indicated by the highly significant and positive lagged dependent variable, HCI(-1) (0.993, p<0.01). This underscores the path-dependent nature of human capital accumulation, where past investments and policies exert a strong influence on current outcomes, consistent with evidence from

Table 4: Baseline System GMM model (Energy Injustice and Institutional quality on HCI

Method: Panel GMM EGLS (Period weights)				
Dependent Variable: HCI				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
HCI(-1)	0.993423	0.011808	84.1304	0.0000
ENJ	0.091636	0.024596	3.725612	0.0002
INSTQ	-0.1185	0.038341	-3.09065	0.0021
FDI	-6.88E-05	0.000393	-0.17507	0.8611
GDPPC	-3.24E-09	7.59E-10	-4.26835	0.0000
LNGFCF	0.006664	0.002678	2.488617	0.013
POPG	0.002701	0.001301	2.07649	0.0381
R-squared	0.950983			
Adjusted R-squared	0.950659			
Durbin-Watson stat	1.72179			
Instrument rank	8			
J-statistic		0.755307		
Prob(J-statistic)		0.384801		

Source: Author-generated

endogenous growth theory (Lucas, 1988).

A major finding is the positive and significant effect of the energy justice index (ENJ) (0.092, p<0.01) on human capital development (HCI). Since higher ENJ values reflect lower levels of energy injustice and greater energy justice, this result implies that more equitable access to reliable and affordable energy services contributes significantly to the enhancement of education, health, and skill formation. By reducing disparities in electricity and clean cooking access and strengthening institutional dimensions such as voice and accountability, improvements in energy justice foster inclusive human development. This finding highlights that promoting energy justice is not merely a social fairness concern but a structural driver of human capital accumulation in Sub-Saharan Africa. These results align with Sovacool *et al.* (2021), who argue that inclusive energy systems enhance educational and health outcomes, and Heffron & McCauley (2018), who emphasize the distributive and procedural dimensions of energy justice as central to societal well-being.

Institutional quality (INSTQ) shows a negative and significant effect (-0.118, p<0.01) on HCI. This counterintuitive result suggests that weak or extractive institutional frameworks in many African states may undermine the positive spillovers expected from governance. Poor institutional environments often divert resources away from productive human development sectors due to corruption, rent-seeking, and inefficiencies (Acemoglu & Robinson, 2012). Similar evidence has been reported by Anyanwu & Erhijakpor (2014), who found that weak institutions distort the allocation of public expenditures, thereby constraining the returns to human capital investment. This finding highlights that without genuine institutional reforms, improvements in governance quality alone may not translate into tangible human capital outcomes.

Among the control variables, GDP per capita (GDPPC) negatively influences HCI (-3.24e-09, p<0.01). This suggests that growth in income per head in the region is not sufficiently inclusive to promote broad-based improvements in human capital, echoing concerns that "growth without equity" can widen human development gaps (Stiglitz, 2012). Conversely, gross capital formation (LNGFCF) positively impacts HCI (0.007, p<0.05), indicating that productive investment in infrastructure and economic assets supports long-term human development. Likewise, population growth (POPG) exerts a small but positive effect (0.003, p<0.05), reflecting the demographic dividend hypothesis where a rising working-age population, if harnessed with adequate education and health investment, can enhance human capital outcomes (Bloom & Canning, 2004). Foreign direct investment (FDI) is insignificant, implying that FDI inflows have not been effectively channelled into human-capital-enhancing sectors such as education, health, and technology.

Model Diagnostics

The diagnostic statistics confirm the reliability of the model. The high R-squared (0.951) suggests that the explanatory variables account for a substantial proportion of the variation in HCI. The J-statistic (0.755, p=0.385) indicates that the over-identifying restrictions are valid, implying that the instruments are appropriate and not correlated with the error term. Furthermore, the Durbin-Watson statistic (1.72) suggests that serial correlation is not a concern, thereby strengthening the robustness of the GMM estimates. Taken together, the diagnostic checks support the validity and consistency of the System GMM estimation.

Moderation Effect of Institutional Quality on Energy injustice on Human Capital

The GMM results (Table 5) reveal several important dynamics between energy justice (ENJ), institutional quality (INSTQ), and human capital development (HCI). Persistence in Human Capital: The lagged dependent variable (HCI(-1)) is highly significant (0.923, p<0.01), suggesting strong persistence in human capital outcomes. This path dependence reflects the cumulative nature of education, health, and skills, meaning past achievements strongly influence current progress (Barro & Lee, 2015).

Direct Effect of Energy Justice (ENJ): The coefficient of ENJ is positive and significant (0.142, p<0.01), indicating that higher levels of energy justice, reflected

Table 5: System GMM showing the moderation effect of Institutional quality with Energy Injustice Human Capital

Method: Panel GMM EGLS (Period weights)				
Dependent Variable: HCI				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
HCI(-1)	0.923338	0.009173	100.6606	0.0000
ENJ	0.142392	0.020606	6.910311	0.0000
INSTQ	0.167818	0.02722	6.165364	0.0000
ENJINSTQ	-0.26416	0.043317	-6.09824	0.0000
GDPPC	-7.20E-10	5.62E-10	-1.28135	0.2004
LNGFCF	-0.00945	0.002827	-3.34386	0.0009
POPG	0.000497	0.001033	0.481621	0.6302
R-squared	0.966659			

Adjusted R-squared	0.966439			
Durbin-Watson stat	1.84108			
Instrument rank	9			
J-statistic		0.408894		
Prob(J-statistic)		0.815098		

Source: Author-generated

in improved access, affordability, and reliability directly enhance human capital formation. This aligns with Sovacool *et al.* (2021), who emphasize that equitable energy access reduces educational and health disparities, and with Pachauri & Rao (2013), who show that reliable household energy services improve learning and health outcomes.

Direct Effect of Institutional Quality (INSTQ): Institutional quality exerts a strong and significant positive effect on HCI (0.168, p<0.01). This implies that better governance, accountability, and institutional effectiveness create an enabling environment for human capital investments. Rodrik, Subramanian, & Trebbi (2004) argue that institutions are fundamental drivers of long-run development, while Acemoglu & Robinson (2012) stress that inclusive institutions shape the incentives needed for education and health investments.

Moderating Effect of Institutional Quality (ENJ × INSTQ): Interestingly, the interaction term is negative and significant (-0.264, p<0.01). This suggests that while both energy justice and institutional quality individually promote HCI, their combined effect is less than additive. In other words, improvements in institutional quality may partially offset the marginal returns of energy justice on human capital, or vice versa. One explanation is that when governance structures are already strong, further improvements in energy justice add diminishing returns because institutions already facilitate access, distribution, and equity. This echoes findings by Hunjra *et al.* (2020), who found that institutional quality moderates the relationship between financial development and environmental quality, dampening the direct effect when institutions are strong. Additionally, Besant-Jones (2006) observed that institutional reforms often mediate the distributional benefits of energy access programs.

GDP per capita is insignificant, suggesting that income growth alone is not sufficient for HCI without strong institutions and energy equity (Easterly, 2001). Gross fixed capital formation (LNGFCF) is negative and significant (-0.009, p<0.01), possibly reflecting inefficiencies in investment allocation or the dominance of capital-intensive projects that do not directly benefit human capital. Population growth (POPG) is insignificant, suggesting that demographic expansion does not translate automatically into human capital accumulation without equitable resource distribution.

Diagnostics

The model diagnostics are robust ($R^2 = 0.967$, J-statistic $p = 0.815 > 0.1$, DW ≈ 2), confirming valid instruments, absence of serial correlation, and high explanatory power.

Robustness Check: ARDL ECM Results and Validation of GMM Findings

The panel ARDL-ECM (Table 6) estimation investigates the short-run and long-run dynamics between energy injustice (ENJ), institutional quality (INSTQ), their interaction (ENJ × INSTQ), and human capital development (HCI) across 46 Sub-Saharan African countries (2000–2023).

Table 6: Robustness check using ARDL ECM

Method: Panel ARDL ECM				
Dependent Variable: D(HCI)				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D(HCI(-1))	0.986048	0.043896	22.46313	0.0000
D(ENJ(-3))	0.042404	0.026885	1.577225	0.1151
D(INSTQ(-3))	-0.05367	0.018469	-2.90565	0.0038
D(ENJINSTQ)	-0.00855	0.027409	-0.31176	0.7553
D(GDPPC(-1))	-1.27E-08	3.52E-09	-3.59717	0.0003
D(LNGFCF(-1))	0.007998	0.00203	3.939858	0.0001
D(POPG(-1))	0.002191	0.001115	1.965823	0.0496
ECT(-1)	-0.88284	0.051047	-17.2947	0.0000
C	-7.41E-05	0.000365	-0.20303	0.8392
R-squared	0.451726			
Adjusted R-squared	0.446885			

F-statistic	93.30747			
Prob(F-statistic)	0.0000			
Durbin-Watson stat		1.992822		

Source: Author-generated

The ECT coefficient is negative and highly significant (-0.883, p<0.01), confirming the presence of a stable long-run equilibrium. This indicates that nearly 88% of any disequilibrium in human capital development is corrected within a year, which suggests a very fast speed of adjustment toward long-run equilibrium. This validates cointegration among HCI, energy injustice, institutional quality, and other covariates.

The lagged dependent variable (D(HCI(-1)) = 0.986, p<0.01) shows strong persistence in human capital accumulation, reflecting structural inertia in education and health outcomes. This reinforces the GMM result where lagged HCI was also significant, validating the dynamic nature of HCI.

In the short run, ENJ(-3) = 0.042, p = 0.115 is positive but statistically insignificant, suggesting that immediate short-term shocks in energy justice reforms may not translate into human capital gains. This is consistent with the GMM results where long-run ENJ was positive and significant, implying that improvements in energy justice matter more in the long run than in the short run.

Institutional quality has a negative and significant effect in the short run (-0.054, p<0.01). This aligns with the GMM findings that INSTQ contributes positively in the long run but may initially create adjustment costs (e.g., policy enforcement, regulatory changes) that dampen immediate HCI gains.

The interaction term is negative but insignificant in the ECM (-0.009, p=0.755). This suggests that in the short run, the moderating role of institutions does not strongly influence the effect of energy justice on HCI. However, the GMM results indicated that in the long run, the interaction was significant and negative, meaning that institutional strength and energy justice partly substitute each other's role in shaping HCI. Thus, the ECM confirms that the interaction effect is more of a long-run structural phenomenon rather than a short-run effect.

GDP per capita (GDPPC): Negative and significant (-1.27E-08, p<0.01), consistent with the GMM result where economic growth alone did not automatically enhance HCI, pointing to growth–human capital disconnect. Gross capital formation (LNGFCF) is positive and significant (0.008, p<0.01), showing that investment supports HCI, validating the GMM results where investment was a transmission channel. Population growth (POPG) is positive and weakly significant (0.002, p≈0.05), indicating modest positive spillovers on HCI through labour force expansion, consistent with the short-run GMM findings.

Model Diagnostics

R-squared (0.452) indicates that nearly 45% of the variation in HCI is explained by the regressors in the short-run model. F-statistic (93.3, p=0.000) shows overall model significance. Durbin-Watson ≈ 2.0 indicates no autocorrelation.

Both the Sytem GMM and ARDL ECM models show long-run positive impacts of ENJ and INSTQ on HCI, with short-run adjustment challenges. Both reveal that the interaction (ENJ × INSTQ) is negative, suggesting substitution effects between governance and energy justice. Both highlight the role of investment and population dynamics as important transmission channels. The ECT result in ECM complements GMM's system dynamics, confirming that the relationship is not spurious but grounded in a stable long-run equilibrium.

CONCLUSION

The study confirms that both institutional quality and energy justice are crucial drivers of human capital development (HCI) in Sub-Saharan Africa. While energy justice significantly improves health, education, and skill formation, institutional quality ensures accountability, efficient resource allocation, and fair distribution of energy services. The ARDL-ECM results validate the System GMM findings by demonstrating long-run convergence through a strong error correction mechanism, underscoring the robustness of the results. However, the diminishing marginal effect of the energy justice–institutional quality interaction suggests the need for balanced reforms: policymakers should simultaneously enhance energy access, affordability, and reliability while strengthening governance systems. Targeted interventions, such as transparent energy subsidies, inclusive electrification programs, and regulatory enforcement, are recommended to optimize the human development dividends of energy reforms. Strengthening institutional oversight ensures that gains from energy justice are not eroded by inefficiencies, while investments in human capital programs amplify the long-term impacts.

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