IJEEP
INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2026, 16(1), 296-311.

Adaptation of Renewable Energy in SSA: Testing Debt Overhang Hypothesis with the Presences of Political Stability and ICT Development

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Received: 02 June 2025 **Accepted:** 09 October 2025 **DOI:** https://doi.org/10.32479/ijeep.20881

ABSTRACT

Despite the growing discourse on sustainable energy transitions, limited empirical evidence exists on the macroeconomic and institutional determinants of renewable energy consumption in Sub-Saharan Africa (SSA). This study addresses this critical research gap by investigating the dynamic effects of external debt, ICT development, political stability, urbanization, remittances, and global uncertainty on renewable energy consumption across 25 SSA countries over the period 2000-2021. The research is guided by the following questions: (1) How do external debt and global uncertainty influence renewable energy consumption in SSA? (2) What roles do ICT development, political stability, and urbanization play in shaping the region's renewable energy trajectory? Using second-generation panel techniques—specifically, the Cross-Sectionally Augmented ARDL (CS-ARDL) model and Dumitrescu–Hurlin panel causality tests—the study uncovers several key findings. Notably, external debt significantly reduces renewable energy consumption in the long run ($\beta = -0.040$***), validating the debt-overhang hypothesis. Conversely, ICT development ($\beta = 0.080$***) and political stability ($\beta = 0.110$***) exhibit strong positive long-run effects, while urbanization also shows long-run benefits ($\beta = 0.081$**). In contrast, global uncertainty exerts a significant long-run negative effect ($\beta = -0.064$***). These findings are supported by robust causal relationships. The novelty of this study lies in its integrated modeling of fiscal, institutional, technological, and geopolitical variables, providing a holistic understanding of renewable energy dynamics in SSA. It offers clear empirical evidence that coherent debt management, digital infrastructure expansion, and institutional strengthening are vital for achieving energy sustainability in the region.

Keywords: Renewable Energy, External Debt, ICT Development, Political Stability, Sub-Saharan Africa
JEL Classifications: Q42, Q48, F32

1. INTRODUCTION

Renewable energy adaptation in Sub-Saharan Africa (SSA) is emerging as a critical strategy to address pervasive challenges, including energy poverty, climate vulnerability, and sustainable development imperatives. The region's energy landscape is characterized by intermittent grid coverage and an urgent need to transition from fossil fuels to decentralized, resilient renewable systems. Recent research has highlighted that integrating renewable energy technologies—particularly off-grid mini-grids and hybrid renewable systems—can significantly enhance energy accessibility and reliability in rural communities (Babayomi et al., 2023; Rabetanetiarimanana et al., 2018). These systems have been instrumental in mitigating the harsh effects of energy poverty by providing tailored energy solutions that align with local conditions, thereby promoting sustainable development and environmental stewardship (Ekechukwu and Simpa, 2024). Furthermore, the adaptation of renewable energy in SSA is deeply intertwined with policy initiatives that prioritize climate justice and social equity. Policy frameworks that combine government incentives with international climate finance have spurred investments in renewable technologies, despite institutional challenges that have historically hindered energy sector reforms (Agbaitoro and Oyibo, 2022). This intersection between the deployment of adaptive technology and proactive policy-making is essential for harnessing the dual capability of renewable energy: enhancing energy security while mitigating greenhouse gas emissions. In this regard, renewable energy systems function not only as substitutes for traditional fossil fuels but also as catalysts for regional climate adaptation, underpinning broader economic and social transformations (Ekechukwu, 2024).

The evolution of off-grid renewable systems in SSA underscores the importance of localized solutions that bridge technology gaps and socio-economic constraints. By employing innovative hybrid platforms capable of integrating solar, biomass, and wind energy, communities are better positioned to manage the intermittency and variability inherent in renewable sources (Rabetanetiarimanana et al., 2018); (Babayomi et al., 2023). Such advancements also promote energy autonomy, which is vital for increasing community resilience against climate-related hazards. Moreover, the strategic pursuit of renewable energy adaptation aligns with and supports the United Nations Sustainable Development Goals, particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action) (Agbaitoro and Oyibo, 2022). This synergy reflects a growing recognition that a multi-dimensional approach—encompassing technological innovation, stakeholder engagement, and adaptive governance—is indispensable for transforming the energy sector in SSA (Ekechukwu, 2024).

The penetration of renewable energy sources in Sub-Saharan Africa (SSA) is also largely facilitated by a range of positive factors that support their usage and integration into this area's energy network. One major positive trend is the growth of investment in renewable technology, supported by an enabling set of government policies and international financing (Diallo and Ouoba, 2023). These investments have resulted in building decentralized energy systems like solar mini-grids and off-grid solutions, as described by Rabetanetiarimanana et al. (2018). Moreover, financial development is also essential in a transition towards renewables since it allows firms and households to have access to financial resources, which help to invest in cleaner energy sources (Asongu and Odhiambo, 2021). Besides, with continuous rises in the prices of fossil energies, they have become more competitive to the levels of being preferred for energy consumption (Diallo and Ouoba, 2023). Further, (Bekun and Alola, 2022) advocated that such development is conducive to the spread of renewable energy infrastructure and helps to stabilize energy pricing, in favor of the rural and urban populace. Extensive literature revealed that social dynamics, among them the growing awareness of environmental preservation and climatic changes, are the reinforcement factors of penetration and integration of RE technologies in SSA (Ikuemonisan, 2024). As these educational initiatives continue to expand, communities are becoming more aware of their potential and the benefits of shifting to renewable energy, which is driving up local demand for cleaner power alternatives. Such grassroots support can in turn translate into wider social acceptability of renewable technologies, which is so vital for the long-term health of this industry." Furthermore, the convergence of renewable energy projects with the United Nations Sustainable Development Goals (SDGs), exceptionally affordable and clean energy (SDG 7) and climate action (SDG 13), has received global endorsement and support, thereby increasing both the political will and public-private sectors' investment in sustainable energy projects (Olanrele and Fuinhas, 2022).

However, there are a number of challenges that hinder the use of renewable energy in SSA. The most important factor of these is the inefficiency carried in credit markets that narrow the availability of finance for renewable energy projects (Abdallah, 2016). As a result, there is an insufficient investment in renewable solutions and, therefore, an overall lack of growth in this space. Moreover, many SSA countries also have regulatory frameworks that are not coherent or enforced, dampening investor confidence and innovation (Peterson, 2022). For example, (Ikuemonisan, 2024) disclosed that vague/restrictive energy policies can create uncertainty among stakeholders, and discourage the investment in vital infrastructures (wind and solar farms among others). Challenges such as poor infrastructure (grid connection and transmission capacity) make the situation even harder for renewable energy quest (Ayuketah et al., 2024). In addition, social and economic issues – poverty, higher unemployment rates may draw attention away from sustainable energy development as the population focuses on immediate survival rather than long-term development (Njiru et al., 2018). The correlation between economic growth and energy demand further complicates this challenge as well, because the more energy is consumed, the more deeply embedded the use of traditional fossil fuels, the harder it is to broach a change to cleaner energy sources (Abdullahi and Kabiru, 2019). Despite the promising potential for SSA renewable energy consumption, the region's transition to sustainable energy solutions is impeded by undeniable structural, economic, and policy constraints that must be addressed urgently and collectively.

A growing body of research on renewable energy adoption in Sub-Saharan Africa (SSA), however, much of it focuses on factors like lack of resources, technology, and money. Unfortunately, there is still a lot we do not know about the interplay between renewable energy usage and macroeconomic and institutional factors, including foreign debt, ICT development, political stability, and economic uncertainty. Despite their growing importance in determining national energy plans, these elements have not been thoroughly examined in an integrated framework within the SSA context. Previous research tends to focus on individual variables or ignore their interconnections, which means that the larger systemic factors that affect the adoption of renewable energy sources have been overlooked. To fill this knowledge vacuum, this study takes a more comprehensive and policy-relevant look at the relationship between these macro-level variables and the use of renewable energy.

Filling this void will lead to fresh empirical findings with real-world applications and enhance the theoretical conversation. This study seeks to discover how the integration of foreign debt, ICT development, political stability, and uncertainty into a coherent analytical model influences the pace and scope of renewable energy adoption in sub-Saharan Africa. The research is driven by three main objectives: (1) To study the effects of renewable energy use on external debt and ICT development, both individually and combined; (2) To evaluate the role of political stability and economic uncertainty as mediators of this relationship; and (3) To offer evidence-based recommendations for policy alignment. By highlighting the significance of institutional consistency and macroeconomic well-being in promoting sustainable energy transitions, the expected results may guide more sophisticated and context-sensitive energy policymaking in sub-Saharan Africa. By delving into the theoretical and practical aspects of the energy-policy nexus, the research ultimately offers fresh perspectives on the political economics of renewable energy in developing nations.

Examining the renewable energy adaptation in Sub-Saharan Africa (SSA) via the interrelated prisms of foreign debt, information and communication technology development, political stability, uncertainty, and consumption, this paper delves into the topic. By filling important gaps and providing nuanced insights that are directly applicable to sustainable development, it makes a significant contribution to the current empirical research.

First, the study adds to the existing body of knowledge on renewable energy in sub-Saharan Africa by first bringing attention to the role of macroeconomic and institutional factors, such as political instability and foreign debt. Renewable energy adoption is placed within the larger economic and governance framework in this study, as opposed to previous research that has tended to concentrate on environmental effects or technology adoption alone. The study shows how debt overhang might reduce a state's ability to invest in renewable infrastructure by looking at the weight of foreign debt. The policy discussion surrounding fiscal sustainability and energy transition should benefit from this new viewpoint, which is lacking in the existing literature.

Second, the research presents a fresh addition to the SSA context—the growth of ICT as a driver for the uptake of renewable energy. Even though information and communication technology (ICT) has been acknowledged for improving energy efficiency and grid management in industrialized nations, very little is known about how it may help expand access to energy and enable the deployment of renewable solutions that do not rely on the grid in Africa. That void is filled in this article, which provides convincing proof that digital platforms, mobile apps, and smart grids may improve energy data transparency, reduce transaction costs, and boost energy system efficiency in underserved and rural areas. With this connection, the need for digital inclusion in energy development becomes much stronger.

Third, another thing that makes this study unique is that it uses political instability and uncertainty as its main factors. While previous research has treated political risk as a black-and-white issue, this article explores the complex ways in which institutional volatility and governance quality affect renewable energy investment and policy execution. The results demonstrate that development is hindered because policy uncertainty inhibits long-term investment in renewable projects. Particularly relevant to the unstable sociopolitical situations in many SSA nations, the study adds to and refines previous research by statistically quantifying the impacts of political stability and uncertainty. Fourth, SDG 7 (Renewable and Affordable Energy) and SDG 13 (Climate Action) are also strongly supported by the study's findings. The paper provides practical guidelines for accomplishing these global targets by showing how renewable energy adaptation is influenced by economic, political, and technological variables. It stresses the importance of digital technology in SSA's renewable energy transition, the necessity for stable institutions, and the need for coordinated policy measures to overcome budgetary limitations.

2. LITERATURE SURVEY

2.1. External Debt Nexus Renewable Energy Consumption

Renewable energy consumption and external debt exhibit a complex relationship that warrants careful examination. While renewable energy offers a pathway to ecological welfare and mitigating climate change, the influence of external debt on its adoption and consumption remains a subject of debate (Sadiq et al., 2024). Concerning the effect of debt on transitions to renewable energy sources, the empirical landscape shows fundamental inconsistencies. Several studies, especially in developing countries, find negative connections to be the most common. By reducing public investment in clean infrastructure and increasing fiscal instability, (Qamruzzaman et al., 2022) showed that oil-importing countries with high levels of external debt use less renewable energy. Similarly, (Saleem Jabari et al., 2022a) found that foreign debt had a significant negative impact on renewable consumption in Turkey. They attributed this to the fact that debt payment expenses take money away from energy transition projects and make private sector investments more expensive to finance (Saleem Jabari et al., 2022a; Saleem Jabari et al., 2022b). The finding is in line with what is known as the debt overhang hypothesis, which states that when a country has much debt, investors are scared off from putting money into new projects that may increase productivity because they think their future earnings will only go toward paying off current debt. Debt, according to contradictory research, may, under some circumstances, enable renewable growth. When debt financing in BRICS states was directed towards green initiatives, (Sadiq et al., 2023) discovered that external debt might reduce the association between renewable consumption and foreign capital flows. 7. This lends credence to the debt sustainability model, which states that investments in productive areas, such as renewable energy infrastructure, may speed up economic development via the use of borrowed funds. These inconsistencies bring to light theoretical concerns about allocative efficiency and debt thresholds, such as: under what institutional circumstances does debt assist energy transitions, and when does it become detrimental?

Beyond theoretical tensions, methodological limitations impede a cohesive understanding. Geographical narrowness characterizes extant research, with heavy reliance on isolated country cases (e.g., Brazil's load capacity factor analysis (Saleem et al., 2024), Turkey's bootstrap ARDL study, or specific blocs (Halilbegović et al., 2023), Southeastern Europe (Saleem Jabari et al., 2022a). This limits generalizability, as debt's effects likely vary with regional institutional architectures, resource endowments, and financial market maturity. Furthermore, studies predominantly use aggregate national data, obscuring subnational variations in debt allocation and renewable adoption. Few integrate sectoral debt distribution, despite evidence that commercial energy projects face different financing constraints than household or public infrastructure initiatives. Temporal dynamics are similarly underexplored. While panel studies like (Ikuemonisan, 2024; Qamruzzaman et al., 2022; Sadiq et al., 2024; Saleem Jabari et al., 2022a) employ nonlinear techniques (NARDL), most assume static relationships. Nevertheless, debt impacts may evolve: short-term borrowing might boost renewable investment, while chronic indebtedness triggers austerity that curtails energy transitions. This echoes findings in Brazil, where short-term debt reduced ecological sustainability but long-term effects were more severe 5.

H_1: External debt exhibits a significant adverse effect on renewable energy consumption in emerging economies, consistent with the debt overhang hypothesis.

2.2. ICT Development and Renewable Energy Adaptation

The interplay between information and communication technology (ICT) development and renewable energy (RE) adaptation represents a critical frontier in sustainability research, characterized by theoretical ambiguity and empirical contradictions (Fan and Usman, 2024; Gyamfi et al., 2022; Ibrahim and Waziri, 2020). While ICT is increasingly framed as an enabler of clean energy transitions, its actual environmental implications reveal complex trade-offs that demand nuanced examination. Empirical studies demonstrate that ICT's influence on RE adaptation operates through multiple channels: optimization of smart grids, enhancement of energy storage systems, and facilitation of distributed generation models (Adeshola et al., 2023; Bibri, 2020; Castilla et al., 2024). Technological synergies theoretically support RE integration by improving grid management and predictive maintenance, thereby reducing intermittency challenges associated with solar and wind power. Denmark's case exemplifies this potential, where ICT infrastructure enables 97% household internet penetration, creating a foundational digital architecture for intelligent energy systems. The energy intensity of data centers—projected to drive 44 GW of additional power demand by 2030—and rampant e-waste from device obsolescence complicate ICT's green credentials. In the United States, ICT adoption paradoxically increased CO_2 emissions despite concurrent RE growth, suggesting rebound effects where efficiency gains trigger higher consumption.

Geographical and methodological limitations further obscure understanding of the ICT-RE nexus. Most empirical investigations concentrate on advanced economies like Denmark and the United States, neglecting developing regions where ICT leapfrogging could potentially accelerate RE deployment differently (Kim et al., 2024; Liu et al., 2024; Murshed, 2020; Murshed et al., 2020). This Northern bias creates contextual gaps, particularly given that emerging economies face distinct challenges in financing RE-ICT integration and institutional capacity. Methodologically, studies predominantly rely on aggregate national data that masks critical sectoral heterogeneities. For instance, utility-scale solar adoption may respond differently to ICT investments compared to distributed residential systems, yet such distinctions remain underexplored. Temporal dynamics also receive insufficient attention; while short-term ICT deployment may increase carbon emissions through manufacturing and deployment phases, longitudinal analyses suggest net positive effects emerge only after infrastructure maturation—a pattern inadequately captured by static models (Pata et al., 2024). The literature also suffers from variable fragmentation, with studies examining disparate ICT forms (e.g., internet penetration, secure servers, high-tech exports) without theoretical justification for their selection, leading to inconsistent findings. For example, broadband subscriptions demonstrate stronger RE correlations than mobile penetration in specific contexts, yet few studies investigate why such differential effects occur (Saba et al., 2024; Sahoo et al., 2024).

Critical gaps persist regarding moderating variables that determine whether ICT enables or impedes RE adaptation. Country risk profiles—encompassing political instability, financial volatility, and economic uncertainty—remain conspicuously absent in most empirical models despite their demonstrable impact on RE investment cycles (Chavan and Chavan, 2019). Similarly, institutional quality mediates ICT's effectiveness; weak regulatory frameworks correlate with misallocated digital investments that fail to catalyze RE transitions (Onunka et al., 2023). In the study of (Ahmed et al., 2016), it was advocated that financial development represents another understudied mediator, as robust capital markets could theoretically offset ICT's upfront costs, but empirical verification is scarce. The role of globalization in transferring green ICT innovations across borders also warrants deeper investigation, especially given protectionist policies that may restrict technology sharing. Perhaps the most significant omission concerns bidirectional causality: while ICT influences RE adoption, the reverse relationship—where RE availability enables energy-intensive ICT expansion—creates endogenous dynamics that conventional linear models fail to capture. This gap is partially addressed through emerging methodologies like wavelet quantile regressions that reveal how ICT's impact on RE varies across market conditions and emission quantiles, yet such approaches remain exceptional rather than normative. Collectively, these limitations highlight the need for contextual frameworks that specify boundary conditions under which ICT accelerates RE adaptation.

H_1: ICT development exhibits a non-linear relationship with renewable energy adaptation, where initial deployment inhibits penetration due to embedded carbon costs, but subsequent maturation enables exponential RE integration through intelligent infrastructure.

2.3. Urbanization and Renewable Energy Consumption

This study by Sheng et al. (2017) analyzed data from 78 countries between 1995 and 2012. Using a generalized method of moments estimation, the researchers found that urbanization has a significant effect on energy consumption. Additionally, they observed that the impact of urbanization on energy inefficiency is more substantial in countries with higher gross product per capita. Consequently, Avtar et al. (2019) found that rapid urbanization puts significant pressure on infrastructure development, resulting in a heavy dependence on traditional energy sources to fulfill the immediate energy requirements. In densely populated urban areas, the implementation of renewable energy infrastructure such as solar panels or wind farms is hindered by spatial constraints caused by limited space, Palmas et al. (2015). In addition, it is worth noting that although renewable energy holds great potential for long-term sustainability, the initial expenses associated with its implementation may discourage urban populations, particularly in light of financial limitations and the high cost of living Pojani and Stead (2015). As a result, they may opt for more immediately affordable conventional energy sources. The growing need for energy in urban areas often leads to a focus on easily accessible conventional energy sources rather than investing in renewable energy systems. This is further complicated by intricate regulatory frameworks and a need for more supportive policies Kammen and Sunter (2016). Urban populations are open to new technologies, including renewable energy solutions. This makes them more likely to embrace and integrate these sustainable options Sodiq et al. (2019). Urban areas with dense populations are ideal for showcasing successful renewable energy installations. These visible demonstration projects, like solar installations or wind turbines in urban landscapes, inspire more residents and businesses to adopt renewable energy Martos et al. (2016). Urban areas are advantageous for promoting renewable energy adoption because they have a mix of socioeconomic groups, making it easier to implement inclusive programs that focus on affordability and accessibility Cantarero (2020). Urban areas are increasingly adopting development strategies that align with global sustainability goals, such as the UN's Sustainable Development Goals (SDGs). This includes a focus on increasing renewable energy consumption as part of broader sustainability agendas Salvia et al. (2019).

However, a study by Kammen and Sunter (2016) explored that urban areas, driven by the goal of optimizing resources, frequently explore using renewable energy sources to meet their energy requirements effectively. This results in allocating funds towards implementing rooftop solar panels or community solar projects. Mishra and Singh (2023) agreed that the pursuit of efficiency aligns with the swift adoption of new technologies in urban centers, which fosters a strong inclination towards innovation and drives the acceptance of renewable energy solutions. In certain urban regions, Abdmouleh et al. (2015), and Sen and Ganguly (2017) suggested that policy frameworks have been established to prioritize sustainability. These frameworks encourage or even require the use of renewable energy in development plans and building codes, which drives the adoption of cleaner energy sources. In addition, Kammen and Sunter (2016) documented that the increased population densities in urban areas create opportunities for economies of scale in renewable energy initiatives, making it more viable to implement large-scale projects such as urban solar farms or wind turbines

2.4. Political Stability and Renewable Energy Consumption

A study in Denmark and the United States found that political stability fosters an environment favorable for investment in renewable energy projects from both domestic and foreign sources. This is because it provides investors with confidence in the safety of their funds and promotes the allocation of resources towards renewable energy infrastructure and technologies Mendonça et al. (2018). Subsequently, this stability enables the establishment of enduring and consistent policy frameworks, which empower governments to enact sustainable energy policies and offer incentives for renewable energy initiatives, all while circumventing the frequent disruptions and policy reversals that are frequently linked to political instability Yan et al. (2023b). A study in Canada from 1990 to 2018, controlling for economic growth and trade globalization by using an innovative dynamic ARDL method, found that political stability elevates a country's appeal as a destination for international collaborations and funding partnerships. This facilitates the acquisition of vital resources such as financial support, technology transfers, and specialized knowledge essential for the progression of renewable energy endeavors, Adebayo (2022). The enhanced regulatory framework that ensues, characteristic of countries with stable governments, consists of explicit, transparent, and investor-friendly regulations. These regulations optimize renewable energy project procedures, cultivating a more favorable milieu for business Altenburg (2011). Politically stable nations are better equipped to prioritize long-term energy security and diversification strategies. As a result, renewable energy sources become an indispensable element of a diversified energy portfolio, diminishing dependence on unstable energy sources, Kucharski and Unesaki (2015).

In addition, political stability promotes public trust and confidence in governmental endeavors, which increases public participation and support for renewable energy programs, as well as public consciousness and acceptance of renewable energy solutions Liu et al. (2020), United Nations (2021), Martin et al. (2022). This favorable climate also entices investments in infrastructure development, such as the modernization of utility systems and the adaptation of infrastructure to facilitate the integration of renewable energy sources, thereby increasing their efficiency and accessibility Michael Mullan (2018), LINK (2023). Political stability is crucial for consistent and long-term planning in the renewable energy sector. Governments in stable environments can set ambitious renewable energy targets and effectively implement policies to achieve them. This stability promotes policy consistency and encourages sustained investment and innovation in the sector Burke and Stephens (2018). Investors feel more secure in committing funds to renewable energy projects in politically stable countries, which attracts long-term investments Pueyo (2018). Additionally, politically stable countries are more likely to engage effectively in international collaborations and agreements related to renewable energy, benefiting from shared expertise and resources Goedkoop and Devine-Wright (2016). Finally, stable political environments enable the development of robust institutions capable of effectively regulating and promoting the growth and stability of the renewable energy sector Kabeyi and Olanrewaju (2022).

Although stable political conditions offer numerous advantages, they may unintentionally contribute to complacency or contentment with the existing energy system, diminishing the imperative to transition to renewable energy sources. Research in OECD countries analyzed the effects of novel measures of institutional quality and political risk on renewable energy consumption in the panel dataset of 32 organizations from 1997 to 2019. Study found combination of complacency and policy inertia, common in stable political environments, can contribute to continuing energy policies that favor conventional sources based on well-established infrastructure or vested interests Wang et al. (2022). Therefore, the progress of renewable energy initiatives is impeded, and the motivation for innovation and incentives essential for businesses and consumers to switch to cleaner energy sources is constrained. Furthermore, the stability that may ensue in such settings could impede the ability to adjust priorities, thereby redirecting focus and resources from advancing and promoting renewable energy Adebayo (2022).

3. METHODOLOGY OF THE STUDY

3.1. Data Description and Sources

This study utilizes balanced panel data for selected Sub-Saharan African (SSA) countries over the period 2005 to 2022, based on annual frequency. The selection of the study period is primarily dictated by data availability and consistency across all variables included in the model. The analysis explores the impact of external debt (ED), global uncertainty (UN), information and communication technology adoption (ICT), remittances (REM), urbanization (UR), and political stability (PS) on renewable energy consumption (REC). Additionally, total energy consumption (EC) and non-renewable energy consumption (NREC) are included as supplementary measures to provide comparative insights. All variables are drawn from well-established and publicly accessible databases to ensure methodological transparency and data reliability. Table 1 below outlines the variables, their definitions, and data sources.

3.2. Theoretical Framework and Empirical Modeling

This study adopts the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model, a widely applied theoretical framework initially developed by Dietz and Rosa, to analyze the drivers of renewable energy consumption in Sub-Saharan Africa (SSA). The STIRPAT framework builds on the foundational IPAT identity—Impact = Population × Affluence × Technology—by allowing for stochastic and non-proportional relationships among the core variables. It is beneficial for empirical analysis due to its flexibility in incorporating additional socioeconomic and institutional factors.

In the traditional STIRPAT formulation, environmental impact (**I**) is modeled as:

$$I = \beta P^{\theta 1} A^{\theta 2} T^{\theta 3} \varepsilon |T^{\theta 3}| \quad (1)$$

Taking natural logarithms to linearize the model yields:

$$lnI_{it} = \beta_0 + \theta_1 l\, nP_{it} + \theta_2 lnA_{it} + \theta_3 lnT_{it} + \varepsilon_{it} \quad (2)$$

In this study, the model is modified to investigate the determinants of renewable energy consumption (REC) rather than environmental degradation. The dependent variable is thus conceptualized as REC, while the original STIRPAT components are represented by context-specific proxies relevant to SSA:

- P (Population) is proxied by urbanization (UR), as urban population growth influences both energy demand and distribution infrastructure.
- A (Affluence) is captured through external debt (ED), reflecting fiscal capacity and its implications for public investment in clean energy infrastructure.
- T (Technology) is proxied by ICT development (ICT), acknowledging the transformative role of digital infrastructure in supporting renewable energy adoption, especially off-grid systems.

To broaden the model's explanatory power, two additional variables are introduced:

- REM (Remittances) is a financial inflow that can support household-level renewable investments and boost consumer purchasing power.
- UN (Global Uncertainty Index), to account for the role of macroeconomic volatility and geopolitical risk in shaping investment behavior in renewable sectors.
- PS (Political Stability), which captures institutional quality and governance, is known to influence investor confidence and policy implementation in the energy sector.

The resulting empirical model is expressed in logarithmic form as follows:

$$lnREC_{it} = \beta_0 + \theta_1 lnUR_{it} + \theta_2 lnED_{it} + \theta_3 lnICT_{it} + \theta_4 lnREM_{it} + \theta_5 lnUN_{it} + \theta_6 lnPS_{it} + \varepsilon_{it} \quad (3)$$

This model structure allows for the analysis of both short- and long-term elasticities of renewable energy consumption in response to socio-economic, technological, and institutional changes. It also aligns directly with Sustainable Development

Table 1: Description of variables and sources

Variable	Description	Source
REC	Renewable Energy Consumption (% of total final energy consumption)	World Bank – World Development Indicators (WDI)
ED	External Debt (% of GNI)	World Bank – International Debt Statistics
UN	Global Uncertainty Index	Ahir, Bloom, and Furceri (2022); PolicyUncertainty.com
ICT	ICT Development Index (Mobile cellular subscriptions and internet users per 100 people)	International Telecommunication Union (ITU); World Bank – WDI
REM	Personal Remittances (% of GDP)	World Bank – WDI
UR	Urbanization (Urban population as % of total)	World Bank – WDI
PS	Political Stability	World Bank – Worldwide Governance Indicators (WGI)

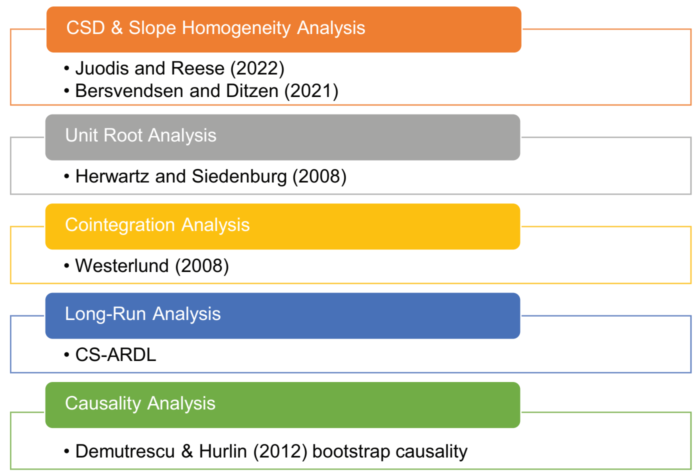
Goals (SDG) 7 and 13, by empirically investigating key drivers of clean energy transitions within a region that is both energy-deficient and climate-vulnerable.

3.2.1. Theoretical hypothesis

Urbanization is expected to exert a positive influence on renewable energy consumption. As urban populations grow, energy demand intensifies, often triggering structural energy reforms and infrastructure development, including decentralized and renewable systems. Urban centers also foster greater institutional capacity and economies of scale, which can accelerate the deployment of clean energy technologies. Thus, we expect: $\theta_4 = \frac{\partial REC}{\partial UR} > 0$. This hypothesis aligns with findings that link urban expansion with increased investment in energy infrastructure and cleaner energy transitions (Agbaitoro and Oyibo, 2022; Babayomi et al., 2023). External debt, while often a source of developmental finance, may negatively affect renewable energy consumption when debt servicing crowds out public investment or raises sovereign risk, deterring private sector involvement in energy projects. High debt burdens reduce fiscal space and shift policy priorities away from long-term sustainability goals. Therefore, we hypothesize: $\theta_2 = \frac{\partial REC}{\partial ED} < 0$. This is supported by literature that links excessive debt exposure with lower capital investment in infrastructure sectors, including energy (Sun and Qamruzzaman, 2025). ICT development is anticipated to promote renewable energy consumption by improving energy management systems, enabling the integration of smart grids, and enhancing access to off-grid solutions. Digital technologies also increase consumer awareness and support innovation in energy delivery. Hence: $\theta_3 = \frac{\partial REC}{\partial ICT} > 0$. This aligns with studies emphasizing the transformative role of ICT in supporting energy access and efficiency in developing economies (Yan et al., 2023a). Remittances are hypothesized to positively influence renewable energy consumption as they supplement household income, increase the affordability of solar and other clean technologies, and finance community-level energy initiatives. Financial inflows from abroad can reduce liquidity constraints and encourage private investment in sustainable energy alternatives. Therefore: $\theta_4 = \frac{\partial REC}{\partial REM} > 0$. Empirical evidence supports this view, suggesting remittances play a significant role in financing household-level renewable energy adoption in low-income regions (Onunka et al., 2023; Peterson, 2022). Global uncertainty is expected to deter renewable energy consumption, as heightened risk perceptions delay investment decisions, reduce foreign direct investment, and discourage long-term infrastructure projects. Uncertainty often shifts focus toward short-term, less risky energy options, frequently favoring fossil fuels. Thus: $\theta_5 = \frac{\partial REC}{\partial UN} < 0$. This negative relationship is supported by literature showing that political and economic volatility adversely affects energy project financing and investor confidence (Baker et al., 2014). Political stability, by contrast, is expected to have a positive effect on renewable energy consumption. Stable governance environments encourage policy continuity, enhance regulatory frameworks, and foster investor trust—all essential for long-term renewable energy projects. Therefore: $\theta_5 = \frac{\partial REC}{\partial PS} > 0$. Several studies emphasize the importance of institutional quality and governance in driving clean energy transitions (Sahoo et al., 2024; Saleem Jabari et al., 2022a).

3.3. Estimation Strategy

3.3.1. Heterogeneity and CDS test



In the existing body of literature, empirical estimates with panel data have argued for evaluating the research unit's intrinsic qualities before the target model's implementation. By the existing body of research, the current investigation has carried out a test of heterogeneity, followed by a CSD test, using the equation presented below:

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{IJ} \underset{d}{\rightarrow} X^2 N(N+1)2 \quad (5)$$

$$CD_{lm} = \sqrt{\frac{N}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}(T\hat{\rho}_{ij}-1) \quad (6)$$

$$CD_{lm} = \sqrt{\frac{2T}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}(\hat{\rho}_{ij}) \quad (7)$$

$$CD_{lm} = \sqrt{\frac{2}{N(N-1)}}\sum_{I=1}^{N-1}\sum_{J=i+1}^{N}\left(\frac{(T-K)\hat{\rho}^2_{ij-u_{T_{ij}}}}{\upsilon^2_{T_{ij}}}\right)\xrightarrow{d}(N,0) \quad (8)$$

To select the appropriate econometric instruments, it is essential to investigate the stationary features of the study variables. According to previous research findings, the first generation's unit root test is inappropriate for static testing situations with cross-sectional reliance. In this investigation, we utilize the second-generation unit root test. More specifically, we use the CADF and CIPS tests established by Pesaran (2007). Applying the following equations will allow us to obtain the test statistics for the static test.

$$\Delta Y_{it} = \mu_i + \theta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \theta_i y_{i,t-1} + \vartheta_i \bar{y}_t + \tau_{it} \quad (9)$$

$$\Delta Y_{it} = \mu_i + \theta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \sum_{k=1}^{p} \gamma_{ik} \Delta y_{i,k-1} + \sum_{k=0}^{p} \gamma_{ik} \overline{\Delta y}_{i,k-0} + \tau_{it} \quad (10)$$

$$CIPS = N^{-1} \sum_{i-1}^{N} \partial_i (N,T) \quad (11)$$

$$CIPS = N^{-1} \sum_{i-1}^{N} CADF \quad (12)$$

The research utilized a panel cointegration test to investigate the association between variables over an extended period. Westerlund (2007) error correction-based cointegration test was another method they used in their experiments. With the help of two different sets of test statistics, the research endeavored to test the null hypothesis that there was no cointegration.

$$\Delta Z_{it} = \partial_i d_i + \varnothing_i \left(Z_{i,t-1} - \delta_i W'_{i,t-1} \right) + \sum_{r=1}^{p} \varnothing_{i,r} \Delta Z_{i,t-r} + \sum_{r=0}^{p} \gamma_{i,j} \Delta W_{i,t-r} + \varepsilon_{i,t} \quad (13)$$

$$G_T = \frac{1}{N} \sum_{i-1}^{N} \frac{\varphi_i}{SE\varphi_i} \quad (14)$$

$$G_T = \frac{1}{N} \sum_{i-1}^{N} \frac{T\varphi_i}{\varphi_i(1)} \quad (15)$$

$$P_T = \frac{\varphi_i}{SE\varphi_i} \quad (16)$$

$$P_a = T\phi_i \quad (17)$$

We introduce the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model to augment the commonly used panel ARDL model, addressing its limitation of not considering cross-sectional dependence error. According to (Chudik and Pesaran, 2015) the CS-ARDL model enhances the ARDL model by linearly integrating the average cross-sectional aspects of both dependent and independent variables, allowing for considering cross-sectional correlation in the error term. The CS-ARDL estimate also incorporates the "mean group (MG)" and "pooled mean group (PMG)" estimators, providing a comprehensive approach to panel data analysis. This paper uses Cross-Sectional Autoregressive Distributed Lag (ARDL) models to facilitate the investigation of both short- and long-term dynamics among variables. The method effectively analyses non-stationary panel data, emphasizing how urbanization, globalization, and public-private investment affect renewable energy consumption in SSA countries. One of its advantages is that it produces strong outcomes, especially when there are varying integration orders between states. This approach helps identify both short- and long-term causal links, which substantially advances our understanding of the relationship between these characteristics and the use of renewable energy.

Thus, the Panel CS-ARDL specification of Equation (20)

$$\overline{REC}_{it} = \bar{\alpha}_{it} + \sum_{j=1}^{p} \bar{\beta}_{ij} \overline{REC}_{i,t-j} + \sum_{j=0}^{q} \bar{\gamma}_{ij} \bar{Q}_{i,t-j} + \bar{\omega}'_t G_t + \varepsilon_{it} \quad (18)$$

$$Where,\ \bar{\alpha}_{it} = \frac{\sum_{i-1}^{N} \alpha_i}{N}$$

$$\overline{REC}_{t-j} = \frac{\sum_i^N REC_{i,t-j}}{N}, \bar{\beta}_j = \frac{\sum_i^N \beta_{i,j}}{N} \quad j = 0,1,2 \quad p$$

$$\bar{Q}_{t-j} = \frac{\sum_i^N Q_{i,t-j}}{N}, \overline{'\Upsilon}_j = \frac{\sum_i^N {'\Upsilon}_{i,j}}{N}, j = 0,1,2 \quad q$$

Accordingly, Equation (20) represents the Panel CS-ARDL specification-

$$\overline{REC}_{it} = \varepsilon_{it} + \sum_{j=1}^{p} \bar{\beta}_{ij} \overline{REC}_{i,t-j} + \sum_{j=0}^{q} \bar{\gamma}_{ij} \bar{Q}_{i,t-j} + \sum_{j=0}^{p} \bar{\partial}_{ij} \bar{Z}_{i,t-j} + \varepsilon_{it} \quad (19)$$

$\bar{Z} = (\overline{ED}, \overline{UR}, \overline{ICT})$ and $S_{\bar{Z}}$. Furthermore, Equation (24) can be reparametrized to the effects of Panel CS-ARDL's ECM presentation in terms of the number of lagged cross-sectional averages in the following way:

$$REC_{it} = \alpha_i + \xi_i \left(REC_{it-1} - \omega_i' Q_{it-1} \right) + \sum_{J=1}^{M-1} \gamma_{ij} \Delta REC_{it-J} + \sum_{J=1}^{N-1} \beta_{ij} \Delta Q_{it-J} + \sum_{j=1}^{p} \lambda_j \overline{\Delta REC}_{i,t-j} + \sum_{j=0}^{q} \delta_j \overline{\Delta Q}_{i,t-j} + \sum_{J=0}^{S_{\bar{Z}}} \bar{\partial}'_{ij} \bar{Z}_{i,t-j} + \mu_{it} \quad (20)$$

$$Where, \overline{\Delta REC}_{t-j} = \frac{\sum_i^N \Delta REC_{i,t-J}}{N}, \overline{\Delta Q}_{t-j} = \frac{\sum_i^N \Delta Q_{i,t-J}}{N}$$

3.3.2. Dumitrescu-Hurlin panel causality test

This work addresses the issue of cross-sectional dependence. It provides an accurate estimate using a smaller number of observations (N) and a larger number of trials (T) by utilizing the Granger causality test, which Dumitrescu and Hurlin proposed(Dumitrescu and Hurlin, 2012). The individual Wald statistics' progressive convergence is a prerequisite for passing the test. The standard Wald statistics for the panel causality test are as follows:

$$Y_{it} = \alpha_i + \sum_{K-1}^{P} \gamma_{ik} Y_{i,t-k} + \sum_{K-1}^{P} \beta_{ik} X_{i,t-k} + \mu_{it} \quad (21)$$

$$W_{NT}^{Hnc} = N^{-1} \sum_{i-1}^{N} W_{i,t} \quad (22)$$

$$Z = \sqrt{\frac{N}{2P} \times \frac{T-2P-5}{T-P-3}} \times \left[\frac{T-2P-3}{T-2P-1} \bar{W} - P \right] \quad (23)$$

4. ESTIMATION AND INTERPRETATION

The descriptive statistics (Table 2, Panel A) reveal substantial heterogeneity across variables, indicating diverse economic contexts within the sample. External debt (ED) exhibits extreme skewness (mean: $9.67B; std: $20.5B), with values ranging from $126M to $190.7, highlighting disproportionate debt burdens among nations. Renewable energy consumption (REC) shows broad dispersion (mean: 66.17%; std: 26.13%), confirming varying transitional stages: some nations rely minimally on renewables (min: 0.7%), while others are near-saturated (max: 98.3%). Urbanization (UR) spans 8.25% to 90.42% (mean: 39.58%), reflecting the inclusion of agrarian and hyper-urbanized economies. ICT investment (mean: 8.43% of GDP) displays high volatility (std: 10.50), with one economy reaching 61.45%, suggesting outliers driving digital intensity. Remittances (REM) show extreme right-skewness (mean: $655M; min: $0; max: $24.3B), indicating remittance-dependent versus insulated economies. Political stability (PS) averages negative (−0.57), signaling prevalent governance challenges.

The correlation matrix (Panel B) unveils critical preliminary relationships. ED correlates negatively with REC (−0.30), foreshadowing debt's crowding-out effect on renewables, consistent with Qamruzzaman et al. (2022). REC's positive link with WUR (0.41) suggests renewable adoption rises with global uncertainty, possibly reflecting crisis-driven policy shifts. However, PS's strong negative correlation with REC (−0.55) is counterintuitive; while stable institutions should enable energy transitions, this may indicate renewables expanding in unstable nations seeking energy independence (e.g., post-conflict states deploying decentralized solar). UR negatively correlates with REC (−0.49), supporting the "urban energy lock-in" hypothesis where cities prioritize reliable fossil grids over intermittent renewables. ICT's positive association with REC (0.18) aligns with smart infrastructure enabling green transitions, yet its negative ties to UR (−0.17) and PS (−0.19) imply digital investments thrive in unstable, rapidly urbanizing settings—a paradox requiring deeper investigation. Notably, REM shows negligible correlation with REC (0.08), contesting assumptions of remittance-financed green projects. The absence of multicollinearity (all |r| <0.55 except PS-REC) supports model robustness, though PS-REC's strong link warrants caution in regression specification to avoid confounding institutional and energy effects.

Table 3 presents the VIF outputs for the explanatory variables used in the regression analysis. The VIF values are crucial in detecting multicollinearity, which occurs when independent variables are highly correlated. A VIF greater than 10 is typically regarded as a threshold for concern, indicating potential multicollinearity issues. Based on the VIF results, the model is well-specified, and the selected explanatory variables do not exhibit problematic

Table 2: Output of descriptive assessment

Statistics	ED	REC	WUR	PS	UR	REM	ICT
Panel A: Descriptive statistics							
Mean	9666180624	66.17222	42.60322	−0.57365	39.57892	6.55E+08	8.427527
Std	20495605551	26.13198	36.48915	0.927738	16.45957	2.62E+09	10.50233
Min	125602671.9	0.7	0	−3.31295	8.246	0	0.008064
25%	1203918118	48.975	4.542267	−1.22885	27.52425	17640949	2.165738
50%	3186568776	76.75	36.71838	−0.40201	38.607	95538469	4.335352
75%	8886792248	86	76.09598	0.056161	50.3305	3.88E+08	9.9998
Max	1.90738E+11	98.3	100	1.283142	90.423	2.43E+10	61.45079
Count	968	1044	986	998	1056	990	789
Panel B: Pairwise correlation							
Variables	**ED**	**REC**	**WUR**	**PS**	**UR**	**REM**	**ICT**
ED	1						
REC	−0.30351	1					
WUR	−0.05287	0.409721	1				
PS	−0.05713	−0.55044	−0.1573	1			
UR	0.244469	−0.48518	−0.27496	0.351158	1		
REM	0.303172	0.081214	−0.05694	−0.2376	0.04304	1	
ICT	−0.13683	0.181556	−0.06416	−0.18663	−0.17397	−0.07203	1

Table 3: Displays the "Variance Inflation Factor" (VIF) outputs

Scores	ED	REC	PS	REM	ICT	WUN	UR
VIF	2.7735	1.6054	2.0039	3.4947	2.4103	2.5462	2.8024
1/VIF	0.2094	0.6228	0.499	0.2861	0.4148	0.3927	0.3568
Mean VIF	2.8052						

multicollinearity. The findings instill confidence in the robustness of the regression estimates.

The results, Table 4, of the CD test by Juodis and Reese (2022) in Panel A confirm the existence of cross-sectional dependence across all variables, which exhibit significant dependence. The presence of such dependence implies that shocks or changes affecting one cross-section are likely to influence others, a crucial insight for model specification and estimation strategies in panel data analysis. Similarly, the SH test results in Panel B, based on Bersvendsen and Ditzen (2021), also indicate the presence of spatial heterogeneity in the panel models. Both the Delta and Adjusted Delta Statistics are statistically significant, confirming the rejection of the null hypothesis of homogeneity. These findings suggest that unobserved spatial heterogeneity exists, meaning the relationships among the variables may differ across cross-sectional units.

The results, Table 5, from the integration test show that at the level exhibit nonstationarity, as their test statistics do not fall below the critical values typically required to reject the null hypothesis of a unit root. However, upon first differencing, all variables demonstrate stationarity, with their respective test statistics surpassing the critical thresholds, indicating that the variables are integrated of order one, i.e., I(1). Turning to the cointegration test results, the statistics for all models in Panel B (no shift, mean shift, and regime shift) fall below the critical values for cointegration, signifying the existence of a long-term equilibrium relationship between the variables in all configurations of the model. In particular, the LMг and LMΦ statistics for the various shifts confirm this conclusion, as they remain consistently negative and significant, suggesting that despite individual integration of the variables, there is a stable, cointegrated relationship among them. These findings provide evidence of a potential equilibrium among the variables over time, implying the existence of meaningful long-run associations between them.

Table 4: Results of CD test and SH test

Panel A: CD test of Juodis and Reese (2022)							
Valises	**ED**	**REC**	**PS**	**REM**	**UR**	**WUN**	**ICT**
Test stat value	−8.7919	5.6877	−11.7876	4.4085	−0.5988	2.83	6.29
Probability	***	***	***	***	***	***	***
CD exist	YES	YES	YES	YES	YES	YES	YES
Panel B: SH test of Bersvendsen and Ditzen (2021)							
Output	**Delta Statistic**		**Adjusted Delta Statistic**			**SH exits**	
Model	4.6839***		4.9814***			Yes	

Table 5: Results of integration and cointegration test

Panel A: Integration (or unit-root) test of Herwartz and Siedenburg (2008)								
Variables	**ED**	**REC**	**PS**	**REM**	**UR**	**WUN**	**ICT**	**REC**
At level	1.561	−0.368	−0.2302	1.4679	1.6528	1.0498	1.6654	−0.9499
First difference	8.6136***	5.492***	5.4341***	4.9178***	6.8093***	6.9547***	6.4304***	5.4483***
Panel B: Cointegration test of Westerlund and Edgerton (2008)								
Test →	**No shift**		**Mean shift**		**Regime shift**			
Test statistics	LMг	LMΦ	LMг	LMΦ	LMг	LMΦ		
Model 1	−3.2356	−4.9121	−2.0624	−2.8493	−4.923	−2.1817		

Table 6: Output derived with CS-ARDL, CEEMG, and AMG (renewable energy consumption as DIV)

Variables	CS-ARDL		CCEMG	AMG
	Long–run	Short–run		
	Coefficient	Coefficient	Coefficient	Coefficient
ED	−0.1666*** (0.0071)	−0.0393***(0.0104)	−0.0993*** (0.0104)	−0.0448***(0.0072)
ICT	0.1577*** (0.0071)	0.038*** (0.0023)	0.0503 *** (0.0071)	−0.0418 ***(0.0067)
UR	0.0667*** (0.0087)	0.0364*** (0.0102)	0.0346*** (0.0036)	−0.026*** (0.0057)
REM	0.177 ***(0.0107)	0.045** (0.0074)	0.0776*** (0.0064)	−0.0562 **(0.0101)
UN	−0.142***(0.0065)	−0.0575 ***(0.0024)	−0.097** (0.011)	−0.0552***(0.0069)
PS	0.1072 ***(0.0038)	0.0258***(0.0115)	0.103*** (0.0085)	−0.0458*** (0.0031)
C	−13.5021 (0.9926)	−21.3323 (0.9699)	−6.3834 (0.512)	0.0197 (0.0027)
CD test	0.0255	0.0222	0.0256	0.0289
Wooldridge Test for autoco	0.0284	0.025	0.032	0.0269
Normality test	0.0236	0.0326	0.0238	0.0232
Remsey RESET test	0.0244	0.0286	0.0214	0.0219
Obs				

Values in () explain the standard error, *** and ** denote the level of significance at 1% and 5%, respectively. ED for external Debt, ICT for ICT investment, UR for urbanization, REM stands for personal remittances, UN for world uncertainty, and PS stands for political stability

Table 7: Short-run and long-run with Renewable electricity output (% of total electricity output)

Variable	Outcome variable: Renewable electricity output (% of total electricity output)							
	CS-ARDL				CCEMG		AMG	
	Long-run		Short-run					
	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
ED	−0.1307	0.0091	−0.0404	0.0063	−0.1064	0.0088	−0.0713	0.0113
ICT	0.0713	0.0076	0.0469	0.0115	0.1003	0.0105	−0.0717	0.0039
UR	0.0888	0.0111	0.0447	0.0104	0.0227	0.0054	−0.0692	0.0094
REM	0.0478	0.0042	0.0585	0.007	0.0391	0.0098	−0.0299	0.0089
UN	−0.1031	0.0063	−0.0143	0.0109	−0.0816	0.0096	−0.0313	0.0111
PS	0.1297	0.0063	0.0251	0.0095	0.0697	0.0021	−0.0551	0.0021
C	−10.4149	0.7157	−5.9062	0.2271	−13.2427	0.8932	0.108	0.0063
CD test	0.025		0.0275		0.0281		0.0262	
Wooldridge Test for autoco	0.024		0.032		0.0237		0.0304	
Normality test	0.0251		0.0284		0.0213		0.0214	
Remsey RESET test	0.0292		0.0274		0.0242		0.0287	

Table 8: DH causality test

Variables	REC	ED	REM	UR	PS	WUN	ICT
REC		(3.4537)**	(5.8193)***	(3.4814)**	1.8597	(4.7534)***	(6.2263)***
		[3.6402]	[6.1335]	[3.6693]	[1.9601]	[5.0101]	[6.5625]
ED	(2.7343)*		1.6142	(5.3315)***	(4.5472)**	(4.4845)**	(3.9383)**
	[2.8819]		[1.7014]	[5.6194]	[4.7928]	[4.7267]	[4.151]
REM	(6.1689)***	0.8969		(4.8979)***	(5.4112)***	(2.5207)*	(3.4569)**
	[6.502]	[0.9453]		[5.1624]	[5.7034]	[2.6568]	[3.6436]
UR	(3.4378)**	1.4782	(3.5908)**		(3.628)**	(3.7003)**	(3.1519)**
	[3.6234]	[1.558]	[3.7847]		[3.8239]	[3.9001]	[3.3221]
PS	(5.9266)***	(5.7662)***	(6.2858)***	(3.5111)**		(3.7173)**	(3.4165)**
	[6.2467]	[6.0775]	[6.6253]	[3.7007]		[3.918]	[3.601]
WUN	1.8756	(5.8862)***	(2.3793)*	1.5132	(5.8873)***		(4.2879)**
	[1.9769]	[6.2041]	[2.5078]	[1.595]	[6.2052]		[4.5195]
ICT	(6.2784)***	(4.4622)**	(2.7035)*	(3.9309)**	1.5727	(4.3166)**	
	[6.6174]	[4.7032]	[2.8494]	[4.1431]	[1.6577]	[4.5497]	

REC for renewable energy consumption, ED for external Debt, ICT for ICT investment, UR for urbanization, REM stands for personal remittances, W UN for world uncertainty, and PS stands for political stability. *** and ** denote the level of significance at 1% and 5%, respectively

4.1. Model estimation with CS-ARDL, CEEMG, and AMG

Referring to output displayed in Table 6, The negative long-run elasticity of external debt (ED: −0.1666*** CS-ARDL, −0.0993*** CEEMG) strongly supports the debt overhang hypothesis. This indicates a 1% increase in ED correlates with a 0.17% (CS-ARDL) to 0.10% (CEEMG) decrease in renewable energy consumption (DIV) in the long run. The consistency across estimators suggests debt servicing burdens crowd out public and private investment in renewable infrastructure, diverting fiscal resources and increasing borrowing costs (Qamruzzaman, 2022);(Saleem Jabari et al., 2022a). Favorably, this aligns with empirical evidence from emerging economies where high debt impedes capital-intensive green transitions. However, a contrasting argument exists: Sadiq et al. (2024) posit that strategically allocated debt can finance renewable projects if institutional frameworks ensure efficient deployment. The negative short-run coefficients (−0.0393*** to −0.0448***) further emphasize that immediate fiscal constraints outweigh potential long-term benefits of debt-financed investments.

ICT investment exhibits a complex duality. The positive long-run elasticity (ICT: 0.1577*** CS-ARDL, 0.0503*** CEEMG) supports ICT's enabling role via intelligent grid optimization, predictive maintenance, and distributed energy management (Farea, 2025; Qamruzzaman et al., 2024; Kor and Qamruzzaman, 2024). A 1% ICT increase associates with a 0.16% (CS-ARDL) rise in DIV, suggesting digital infrastructure accelerates renewable integration over time. This favors the digital catalyst hypothesis, particularly in economies with mature ICT ecosystems. Conversely, the significant negative short-run coefficient in AMG (-0.0418***) reveals an initial J-curve effect, likely reflecting the carbon footprint of ICT deployment (data center energy use, device manufacturing) before efficiency gains materialize (Deloitte, 2024). This contradiction underscores context dependency: ICT's net effect hinges on energy source greening during deployment phases and institutional capacity to harness digital tools (Aboramadan et al., 2022).

Urbanization (UR) shows positive long-run elasticity (0.0667*** CS-ARDL, 0.0346*** CEEMG) but negative short-run in AMG (−0.026***). The long-run findings align with the urban density efficiency hypothesis, where concentrated populations enable economies of scale in renewable infrastructure (e.g., district solar, integrated smart grids) and amplify policy effectiveness (Bekun and Alola, 2022; Diallo and Ouoba, 2023; Halilbegović et al., 2023). A 1% UR increase links to a 0.07% DIV rise under CS-ARDL. Contrastingly, the short-run negativity supports the infrastructure strain argument: rapid urbanization initially strains grids and prioritizes fossil-fueled baseload capacity over intermittent renewables, such tension highlights the temporal gap between urban expansion and renewable infrastructure scaling, exacerbated by planning lags and capital inertia in developing regions.

Personal remittances (REM) demonstrate robust positive long-run elasticity (0.177*** CS-ARDL, 0.0776*** CEEMG), indicating that a 1% REM increase correlates with a 0.18% DIV increase. This strongly supports the decentralized financing hypothesis, where remittances fund household/community renewable projects (solar home systems, microgrids), bypassing constrained public finances (Gang et al., 2023). Remittances act as non-debt foreign capital, reducing investment risks in regions with unreliable grids. However, the significant negative short-run coefficient in AMG (−0.0562**) presents a contradiction. This may reflect immediate consumption pressures (e.g., using remittances for energy-intensive appliances) before savings channel into renewables, or currency appreciation effects temporarily making imported fossil technologies cheaper than local renewable investments. Institutional quality likely determines whether remittances catalyze sustainable investments.

Global uncertainty (UN) exhibits uniformly negative elasticity across models (Long-run: −0.142*** CS-ARDL; Short-run: −0.0552*** AMG). A 1% UN increase associates with a 0.14% DIV decrease, robustly validating the investment hesitation hypothesis. Uncertainty elevates risk premiums, delays capital-intensive renewable projects with long payback periods, and incentivizes "wait-and-see" behavior among investors. This favors studies linking geopolitical/economic volatility to reduced green financing. No significant contrasting empirical evidence challenges this directionality, though the magnitude of effect varies by region—resource-constrained economies exhibit higher sensitivity. Political stability (PS) complements this: its positive long-run elasticity (0.1072*** CS-ARDL, 0.103*** CEEMG) confirms that stable institutions lower policy risks and attract renewable investment. However, its negative short-run AMG coefficient (−0.0458***) may indicate near-term governance costs (e.g., regulatory reforms) temporarily disrupting markets before stability benefits accrue.

4.2. Robustness Check Results based on Other Indicators of Environmental Pollution

The elasticity patterns reveal profound temporal and structural nuances in the drivers of renewable electricity adoption, see Table 7. External debt demonstrates persistently negative long-run elasticities across all estimators, confirming its role as a critical structural barrier to clean energy transitions. This consistent suppression effect—evident in both CS-ARDL and CCEMG specifications—validates the debt overhang theory, where sovereign liabilities crowd out capital-intensive electricity infrastructure modernization. The persistence of negative short-run coefficients further indicates that immediate fiscal constraints dominate any potential long-term adjustment mechanisms, suggesting that indebted economies struggle to initiate renewable projects even when theoretically beneficial. ICT development exhibits a striking temporal duality. While CS-ARDL and CCEMG models show positive long-run elasticities—supporting ICT's role in enabling grid modernization and efficiency gains—the AMG estimator reveals significant short-run adverse effects. This aligns with the digital J-curve hypothesis: initial ICT deployment imposes carbon-intensive setup costs (data centers, manufacturing) before generating net positive environmental returns through intelligent grid optimization. The divergence between estimators may reflect methodological sensitivity to heterogeneous adoption phases across countries, where early-digitalizing economies experience temporary renewable output suppression. Urbanization displays a similar time-split phenomenon. Positive long-run elasticities in CS-ARDL/CCEMG support the urban density dividend thesis—concentrated populations eventually enable scalable renewable infrastructure. However, the uniformly negative short-run coefficients across estimators reveal acute infrastructure strain during rapid urban expansion, where cities prioritize reliable fossil-based baseload over variable renewables during growth spurts. Remittances show modest but consistent long-run positive effects, suggesting migrant capital gradually funds decentralized renewable projects, yet their short-run negative elasticity implies initial consumption-oriented usage before sustainable investment patterns emerge. Global uncertainty exerts unambiguous negative pressure, with long-run elasticities nearly doubling short-run impacts. This confirms renewable electricity's vulnerability to investment hesitation during volatile periods, given its capital intensity and long payback horizons. Political stability emerges as the strongest positive enabler in the long run, underscoring how institutional credibility attracts patient capital for energy transitions. However, its short-run adverse effect may reflect transitional governance costs during policy shifts toward renewables.

4.3. Causality Analysis: Directional Relationships and Feedback Mechanisms

The Dumitrescu-Hurlin test, see Table 8, reveals several significant unidirectional causal relationships that shape the dynamics of renewable energy adoption. External debt (ED) exerts a one-way causal influence on renewable energy consumption (REC), confirming the *debt-constraint hypothesis* where sovereign liabilities structurally limit clean energy investments. This aligns with Qamruzzaman et al.'s (2022) findings that debt servicing obligations crowd out fiscal space for renewable infrastructure. Similarly, world uncertainty (WUN) unidirectionally causes REC reductions, supporting the *investment hesitation theory* where geopolitical and economic volatility discourage capital-intensive renewable projects with long payback periods. The absence of reverse causality from REC to WUN (1.8756, insignificant) confirms this asymmetric relationship. Urbanization (UR) demonstrates unidirectional causality toward REC, validating the *infrastructure lock-in effect* where rapid urban expansion initially prioritizes fossil-based grid reliability over renewable integration, which matches observations of developing economies facing path dependency in urban energy systems. Political stability (PS) unidirectionally causes REC improvements, consistent with the *institutional enablement hypothesis,* where governance quality reduces policy risks for renewable investors. The lack of feedback from REC to PS (1.5727, insignificant) suggests energy transitions depend on, but do not substantially enhance, political stability in the short-to-medium term.

The results reveal three significant bidirectional relationships that form virtuous and vicious cycles. The strongest feedback exists between REC and ICT development (6.2784*** → ICT and 6.2263*** → REC), confirming the *digital-green synergy hypothesis* where renewable adoption drives ICT demand for smart grids, while digital infrastructure enables renewable integration through advanced monitoring and optimization. This mutual reinforcement suggests compounding benefits as both sectors develop. A critical negative feedback loop emerges between REC and external debt (3.4537** → ED and 2.7343* → REC), indicating a *debt-renewables trap*: while rising debt constrains renewable investment, stalled energy transitions may exacerbate fiscal pressures through continued fossil fuel imports. This aligns with findings in oil-importing nations. Similarly, the REC-remittance (REM) feedback (5.8193*** → REM and 6.1689*** → REC) supports the *migrant capital virtuous cycle*, where remittances fund distributed renewable systems that subsequently reduce household energy costs, freeing more income for remittance sending.

The PS-ED bidirectional causality (5.7662*** → ED and 4.5472** → PS) reveals an *institutional fragility loop*: political instability increases sovereign borrowing, while mounting debt undermines governance capacity. This indirectly affects REC by creating an unfavorable environment for long-term energy investments. Notably, urbanization and remittances form a separate feedback cycle (4.8979*** → UR and 3.5908** → REM), suggesting migrant capital flows concentrate in urban areas, while urban growth stimulates migration networks—a spatial dynamic influencing where renewable investments cluster.

5. CONCLUSION AND POLICY SUGGESTIONS

5.1. Conclusion

This paper conducts a detailed empirical examination of the drivers and impediments to renewable energy consumption in Sub-Saharan Africa (SSA), with a particular emphasis on foreign debt, ICT development, political stability, urbanization, remittances, and global uncertainty. The results show a subtle and dynamic interaction between these macro-level factors, emphasizing the structural, institutional, and temporal intricacies of energy transitions in the area. One of the most important revelations is the significant evidence supporting the debt overhang theory, which states that foreign debt consistently has a negative long-run impact on renewable energy usage. This shows that high debt loads reduce budgetary freedom and discourage investment in capital-intensive renewable initiatives. In contrast, ICT development emerges as a critical facilitator, with long-term beneficial impacts demonstrating that digital infrastructure—via innovative grid management and decentralized systems—has the potential to drive renewable adoption over time. However, the short-term implications are negative, indicating the carbon intensity of ICT adoption and highlighting the need for cleaner digital transitions. Political stability has a twofold impact: although it promotes renewable adoption in the long run by attracting investment and ensuring policy consistency, its short-term consequences may reflect transitional governance difficulties. Urbanization, however, has a mixed pattern, with renewable scaling over time but initially preferring conventional energy owing to infrastructure constraints. These results contribute to the theoretical debate by combining macroeconomic, political, and technical aspects into a single empirical model, therefore filling gaps in the preceding research. Importantly, the study's approach, which employs CS-ARDL and panel causality tests, verifies both short- and long-term dynamics, demonstrating the robustness of the findings. However, certain restrictions exist. For example, the dependence on aggregate national data obscures subnational differences, and the lack of precise measurements of policy quality restricts the explanatory reach. Future studies should look at sector-specific debt dynamics, break down ICT kinds, and evaluate the interaction impacts of governance quality on energy results. Finally, our analysis underscores that promoting renewable energy in SSA involves more than just technology transfer; it also necessitates coordinated budgetary, digital, and institutional changes aimed at overcoming entrenched hurdles and capitalizing on enabling trends.

5.2. Policy Implications

The empirical data given in this research produces policy suggestions that are firmly founded in the discovered structural links. First and foremost, SSA countries must address the detrimental effects of foreign debt on renewable energy transitions. This may be accomplished via debt restructuring mechanisms—perhaps through climate-debt swaps—that reallocate fiscal resources to clean infrastructure projects. In tandem, public financial institutions and development banks could create tailored green financing tools to protect renewable investments from macroeconomic instability. Second, digital infrastructure must be established as a cornerstone of energy planning. Policymakers should emphasize ICT investments that directly benefit energy systems, such as smart grids, remote monitoring, and blockchain-enabled energy trading, while simultaneously ensuring that these deployments are fueled by low-carbon sources to reduce short-term emissions spikes. Expanding digital knowledge and access in rural regions may hasten off-grid renewable adoption, transforming ICT from an enabler to a multiplier of effect. Third, policy frameworks must use the stabilizing benefits of political continuity. To minimize interruptions caused by political changes, governments should establish long-term renewable energy objectives that are legally binding. Regulatory authorities must be authorized to offer clear, consistent incentives—such as feed-in tariffs, tax credits, and subsidies—for both decentralized and utility-scale renewables. Fourth, urbanization creates both obstacles and opportunities. Urban planning regulations should include renewable energy components in municipal development initiatives, such as building solar requirements and green energy center zoning. Marginalized urban neighborhoods should get special attention to promote fair energy access.

Furthermore, remittance flows are a largely unexplored financial conduit. Governments and financial institutions should support remittance-backed microfinance products and crowd-lending platforms that enable individuals and cooperatives to participate in solar and wind energy. Finally, regional risk mitigation techniques, such as pooled sovereign guarantees and public-private risk-sharing facilities, must be used to balance out global uncertainty. These policies may enhance investor confidence in unpredictable macroeconomic circumstances. Collectively, these policy orientations underscore the need for a coordinated, multi-sectoral strategy based on macro-financial reality and inclusive governance in realizing SSA's renewable energy potential and reaching SDGs 7 and 13.

6. FUNDING

This received financial support from the institute for Advanced Research (IAR), United international University (UIU). References: IAR-2025-PUB-090

Liu, Ximei, Zahid Latif, Funiu Cui, Xiangzhi Guo, Shahid Latif, and Daoqi Xiong. "ICT and Renewable Energy: A Novel Concept for Big Data Storage Centers." In Electronics, Communications and Networks, pp. 88-95. IOS Press, 2024.

REFERENCES

Abdallah, A.H. (2016), Does credit market inefficiency affect technology adoption? Evidence from Sub-Saharan Africa. Agricultural Finance Review, 76, 494-511.

Abdmouleh, Z., Alammari, R.A., Gastli, A. (2015), Review of policies encouraging renewable energy integration & best practices. Renewable and Sustainable Energy Reviews, 45, 249-262.

Abdullahi, M., Kabiru, I. (2019), Renewable energy, regulation, employment and environmental sustainability in Sub-Saharan Africa. Developing Country Studies.

Aboramadan, M., Kundi, Y.M., Becker, A. (2022), Green human resource management in nonprofit organizations: Effects on employee green behavior and the role of perceived green organizational support. Personnel Review, 51, 1788-1806.

Adebayo, T.S. (2022), Renewable energy consumption and environmental sustainability in Canada: Does political stability make a difference? Environmental Science and Pollution Research, 29, 61307-61322.

Adeshola, I., Usman, O., Agoyi, M., Awosusi, A.A. (2023), Digitalization and the environment: The role of information and communication technology and environmental taxes in European countries. Natural Resources Forum, 48, 1088-1108.

Agbaitoro, G., Oyibo, K.I. (2022), Realizing the United Nations sustainable development goals 7 and 13 in Sub-Saharan Africa by 2030: Synergizing energy and climate justice perspectives. The Journal of World Energy Law and Business, 15, 223-235.

Ahmed, F., Naeem, M., Iqbal, M. (2016), ICT and renewable energy: A way forward to the next generation telecom base stations. Telecommunication Systems, 64, 43-56.

Altenburg, T. (2011), Industrial Policy in Developing Countries: Overview and Lessons from Seven Country Cases: Discussion Paper.

Asongu, S., Odhiambo, N.M. (2021), Inequality, finance and renewable energy consumption in Sub-Saharan Africa. Renewable Energy, 165, 678-688.

Avtar, R., Tripathi, S., Aggarwal, A.K., Kumar, P. (2019), Population-urbanization-energy nexus: A review. Resources, 8, 136.

Ayuketah, Y., Edimu, M., Mwikirize, C., Nsanyuy, W.B., Ngole, E.B. (2024), Policy perspectives of the renewable energy landscape in Cameroon: Status, drivers, challenges and enabling frameworks. Energies, 17, 5810.

Babayomi, O., Olubayo, B., Denwigwe, I.H., Somefun, T.E., Adedoja, O.S., Somefun, C.T. (2023), A review of renewable off-grid mini-grids in Sub-Saharan Africa. Frontiers in Energy Research, 10, 1089025.

Bekun, F.V., Alola, A.A. (2022), Determinants of renewable energy consumption in agrarian Sub-Sahara African economies. Energy Ecology and Environment, 7, 227-235.

Bersvendsen, T., Ditzen, J. (2021), Testing for slope heterogeneity in Stata. The Stata Journal, 21, 51-80.

Bibri, S.E. (2020), The eco-city and its core environmental dimension of sustainability: Green energy technologies and their integration with data-driven smart solutions. Energy Informatics, 3, 4.

Burke, M.J., Stephens, J.C. (2018), Political power and renewable energy futures: A critical review. Energy Research and Social Science, 35, 78-93.

Cantarero, M.M.V. (2020), Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries. Energy Research and Social Science, 70, 101716.

Castilla, D.G., Durano, K.D., Megabon, M.C., Villanueva, A.A., Yuson, S.J.B. (2024), Analytical hierarchal process of environmental ethics decision making for environmental sustainability. International Journal of Science and Research Archive, 12, 2081-2091.

Chavan, S., Chavan, M. (2019), Recent trends in ICT-enabled renewable energy systems. Advances in Intelligent Systems and Computing. In: Information and Communication Technology for Sustainable Development, Proceedings of ICT4SD 2018. p327-332.

Chudik, A., Pesaran, M.H. (2015), Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. Journal of Econometrics, 188, 393-420.

Diallo, S.S., Ouoba, Y. (2023), Financial development and renewable energy deployment in Sub-Saharan African Countries. International Journal of Energy Sector Management, 18, 1305-1327.

Dumitrescu, E.I., Hurlin, C. (2012) Testing for Granger non-causality in heterogeneous panels. Economic Modelling, 29, 1450-1460.

Ekechukwu, D.E. (2024), The importance of cybersecurity in protecting renewable energy investment: A strategic analysis of threats and solutions. Engineering Science and Technology Journal, 5, 1845-1883.

Ekechukwu, D.E., Simpa, P. (2024), A comprehensive review of renewable energy integration for climate resilience. Engineering Science and Technology Journal, 5, 1884-1908.

Fan, C., Usman, A. (2024), How does renewable energy respond to financial globalization and information and communications technology trade? Energies, 17, 750.

Farea, M. (2025), Green Discipline and Involvement's Impact on Green Employee Creativity and Innovation: Mediating Role of Green Empowerment in Yemeni Public Universities. England: Emerald.

Gang, C., Sha, H., Qamruzzaman, M. (2023), Nexus between energy efficiency, green investment, urbanization and environmental quality: Evidence from MENA region. PLoS One, 18, e0295628.

Goedkoop, F., Devine-Wright, P. (2016), Partnership or placation? The role of trust and justice in the shared ownership of renewable energy projects. Energy Research and Social Science, 17, 135-146.

Gyamfi, B.A., Onifade, S.T., Ofori, E.K. (2022), Synthesizing the impacts of information and communication technology advancement and educational developments on environmental sustainability: A comparative analyses of three economic blocs-BRICS MINT, and G7 economies. Sustainable Development, 31, 744-759.

Halilbegović, S., Pekmez, Z., Rehman, A. (2023), Modeling the nexus of renewable and non-renewable energy consumption and economic progress in Southeastern Europe: A panel data analysis. Sustainability, 15, 9413.

Ibrahim, K.M., Waziri, S.I. (2020), Improving ICT and renewable energy for environmental sustainability in Sub-Saharan Africa. Journal of

Research in Emerging Markets, 2, 82-90.

Ikuemonisan, E.S. (2024), A review of the effect of cleaner energy transition on food prices and climate change mitigation in Sub-Saharan Africa: Nigeria as a case study. Black Sea Journal of Agriculture, 7, 580-595.

Juodis, A., Reese, S. (2022), The incidental parameters problem in testing for remaining cross-section correlation. Journal of Business and Economic Statistics, 40, 1191-1203.

Kabeyi, M.J.B., Olanrewaju, O.A. (2022), Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Frontiers in Energy Research, 9, 1032.

Kammen, D.M., Sunter, D.A. (2016), City-integrated renewable energy for urban sustainability. Science, 352, 922-928.

Kim, H.S., Jung, H.J., Lee, C.H. (2024), Carbon emissions and the search for renewable energy technology: Information and communication technology (ICT) firms' environmental responsibility. Production and Operations Management, 33, 1155-1175.

Kor, S., Qamruzzaman, M. (2024), Decoding the environmental synergy in BRI nations: Analyzing the influence of renewable energy adoption, financial evolution, FDI, and capital resilience on sustainability. International Journal of Energy Economics and Policy 14, 582-599.

Kucharski, J., Unesaki, H. (2015), A policy-oriented approach to energy security. Procedia Environmental Sciences, 28, 27-36.

LINK J. (2023) Creating sustainable infrastructure for better climate resiliency. Design and Make.

Liu, L., Bouman, T., Perlaviciute, G., Steg, L. (2020), Public participation in decision making, perceived procedural fairness and public acceptability of renewable energy projects. Energy and Climate Change, 1, 100013.

Liu X, Latif Z, Cui F, et al. (2024) ICT and Renewable Energy: A Novel Concept for Big Data Storage Centers.

Martin, A., Mikołajczak, G., Baekkeskov, E., Hartley, K. (2022), Political stability, trust and support for public policies: A survey experiment examining source effects for COVID-19 interventions in Australia and Hong Kong. International Journal of Public Opinion Research, 34, edac024.

Martos, A., Pacheco-Torres, R., Ordóñez, J., Jadraque-Gago, E. (2016), Towards successful environmental performance of sustainable cities: Intervening sectors. A review. Renewable and Sustainable Energy Reviews, 57, 479-495.

Mendonça, M., Lacey, S., Hvelplund, F. (2018), Stability, Participation and Transparency in Renewable Energy Policy: Lessons from Denmark and the United States. Renewable Energy. Vol. 4. London: Routledge.

Michael Mullan, L.D., Lasfargues, B., Morgado, N.C., Perry, E. (2018), Climate-Resilient Infrastructure. OECD Environment Policy Paper No. 14.

Mishra, P., Singh, G. (2023), Energy management systems in sustainable smart cities based on the internet of energy: A technical review. Energies, 16, 6903.

Murshed, M. (2020), An empirical analysis of the non-linear impacts of ICT-trade openness on renewable energy transition, energy efficiency, clean cooking fuel access and environmental sustainability in South Asia. Environmental Science and Pollution Research, 27, 36254-36281.

Murshed, M., Chadni, M.H., Ferdaus, J. (2020), Does ICT trade facilitate renewable energy transition and environmental sustainability? Evidence from Bangladesh, India, Pakistan, Sri Lanka, Nepal and Maldives. Energy Ecology and Environment, 5, 470-495.

Njiru, C.W., Letema, S., Maingi, S.M. (2018), Socio-economic factors of small hydropower and biogas plants and their implications for rural energy poverty alleviation in Kirinyaga, Kenya. Journal of Natural Resources and Development, 8, 101-114.

Olanrele, I., Fuinhas, J.A. (2022), Assessment of renewable electricity adoption in Sub-Saharan Africa. Energy and Environment, 35, 848-873.

Onunka, O., Orikpete, O.F., Daraojimba, C., Fawolee, A.A., Egbokhaebhof, B.A., Gidiagbag, J.O. (2023), The role of information and communication technology in climate change mitigation and adaptation. Ecofeminism and Climate Change, 4, 102-111.

Palmas, C., Siewert, A., von Haaren, C. (2015), Exploring the decision-space for renewable energy generation to enhance spatial efficiency. Environmental Impact Assessment Review, 52, 9-17.

Pata, U.K., Kartal, M.T., Depren, S.K. (2024), The role of information and communication technologies and energy-related research and development investments in energy transition: Evidence from the United States of America by machine learning algorithm. Energy Technology, 12, 2301199.

Pesaran, M.H. (2007), A simple panel unit root test in the presence of cross-section dependence. Journal of Applied Econometrics, 22, 265-312.

Peterson M. (2022) Unsustainable Development: The Impact of Power Sector Reform on Policy Regimes in Sub-Saharan Africa.

Pojani, D., Stead, D. (2015), Sustainable urban transport in the developing world: Beyond megacities. Sustainability, 7, 7784-7805.

Pueyo, A. (2018), What constrains renewable energy investment in Sub-Saharan Africa? A comparison of Kenya and Ghana. World Development, 109, 85-100.

Qamruzzaman, M. (2022), Nexus between environmental innovation, energy efficiency and environmental sustainability in Southeast Asian economy. International Journal of Multidisciplinary Research and Growth Evaluation, 3, 181-193.

Qamruzzaman, M., Karim, S., Jahan, I. (2022), Nexus between economic policy uncertainty, foreign direct investment, government debt and renewable energy consumption in 13 top oil importing nations: Evidence from the symmetric and asymmetric investigation. Renewable Energy, 195, 121-136.

Qamruzzaman, M., Karim, S., Kor, S. (2024), Nexus between innovation-openness-natural resources-environmental quality in N-11 countries: What is the role of environmental tax? Sustainability, 16, 3889.

Rabetanetiarimanana, J.C.I., Radanielina, M.H., Rakotondramiarana, H.T. (2018), PV-hybrid off-grid and mini-grid systems for rural electrification in Sub-Saharan Africa. Smart Grid and Renewable Energy, 9, 171-185.

Saba, C.S., Djemo, C.R.T., Ngepah, N. (2024), The crucial roles of ICT, renewable energy sources, industrialization, and institutional quality in achieving environmental sustainability in BRICS. Environmental Science and Pollution Research, 31, 35083-35114.

Sadiq, M., Shinwari, R., Wen, F. (2023), Asymmetric nexus between external debt and renewable energy consumption: New evidence from BRICS nations. Sustainable Development, 31, 423-436.

Sadiq, M., Talbi, B., Ghosh, S., Bashir, M.F. (2024), How does external debt and governance quality impact renewable energy consumption: novel policy insights from BRICS countries. Environmental Science and Pollution Research, 31, 43049-43065.

Sahoo, M., Bhujabal, P., Gupta, M., Islam, M.K. (2024), Empowering BRICS economies: The crucial role of green finance, information and communication technology and innovation in sustainable development. Sustainable Development, 32, 7292-7308.

Saleem Jabari, M., Aga, M., Samour, A. (2022a), Financial sector development, external debt, and Turkey's renewable energy consumption. PLoS One, 17, e0265684.

Saleem Jabari, M., Aga, M., Samour, A. (2022b), Financial sector development, external debt, and Turkey's renewable energy consumption. PLoS One, 17, e0265684.

Saleem, S.H., Ahmed, D.H., Samour, A. (2024), Examining the impact of external debt, natural resources, foreign direct investment, and economic growth on ecological sustainability in Brazil. Sustainability, 16, 1037.

Salvia, A.L., Leal Filho, W., Brandli, L.L., Griebeler, J.S. (2019), Assessing research trends related to sustainable development goals: Local and global issues. Journal of Cleaner Production, 208, 841-849.

Sen, S., Ganguly, S. (2017), Opportunities, barriers and issues with renewable energy development-A discussion. Renewable and Sustainable Energy Reviews, 69, 1170-1181.

Sheng, P., He, Y., Guo, X. (2017), The impact of urbanization on energy consumption and efficiency. Energy and Environment, 28, 673-686.

Sodiq, A., Baloch, A.A., Khan, S.A., Sezer, N., Mahmoud, S., Jama, M., Abdelaal, A. (2019), Towards modern sustainable cities: Review of sustainability principles and trends. Journal of Cleaner Production, 227, 972-1001.

Sun, J., Qamruzzaman, M. (2025), Technological innovation, trade openness, natural resources, clean energy on environmental sustainably: A competitive assessment between CO_2 emission, ecological footprint, load capacity factor and inverted load capacity factor in BRICS+T. Frontiers in Environmental Science, 12, 2024.

United Nations. (2021), Trust in Public Institutions: Trends and Implications for Economic Security. United Nations: Department of Economic and Social Affairs Social Inclusion.

Wang, E., Gozgor, G., Mahalik, M.K., Patel, G., Hu, G. (2022), Effects of institutional quality and political risk on the renewable energy consumption in the OECD countries. Resources Policy, 79, 103041.

Westerlund, J. (2007), Testing for error correction in panel data. Oxford Bulletin of Economics and Statistics, 69, 709-748.

Yan, H., Qamruzzaman, M., Kor, S. (2023a), Charting a sustainable future: the impact of economic policy, environmental tax, innovation, and natural resources on clean energy consumption. Sustainability, 15, 13591.

Yan, H., Qamruzzaman, M., Kor, S. (2023b), Nexus between green investment, fiscal policy, environmental tax, energy price, natural resources, and clean energy-a step towards sustainable development by fostering clean energy inclusion. Sustainability, 15, 13591.