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The Symmetric and Asymmetric Effects of ICT on Green Growth in African Countries: Does Renewable Energy Consumption Matter?

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Abstract. This paper investigates the relationship between the diffusion of information and communication technology (ICT) and green growth in African countries. Encouraging financial innovation can promote the adoption of renewable energy, thereby boosting green growth in these countries. Utilizing a nonlinear autoregressive distributed lag (NARDL) panel modelling approach, we analyse the impacts of these variables on green economic growth. The results reveal that renewable energy consumption has a negative effect on green economic growth. Similarly, financial development exhibits a negative correlation with green economic growth, potentially due to factors such as financial sector weaknesses, macroeconomic volatility, financial crises, and nonlinear dynamics. Conversely, ICT diffusion positively and significantly influences GDP. Both renewable energy and ICT diffusion emerge as crucial factors for enhancing economic activity, job creation, and environmental improvement. These findings highlight the need for targeted financial policies to strengthen the financial sector's role in supporting green initiatives. Policymakers should prioritize regulatory frameworks that enhance financial stability and promote sustainable investments. Additionally, future research could explore more granular data and alternative methodologies to further examine the dynamic interactions between ICT, financial development, and environmental sustainability.

1. INTRODUCTION

A green economy is one that is low in carbon, uses resources efficiently, and is socially inclusive. Employment and income growth in a green economy are driven by public and private investment in economic activities, infrastructure, and assets that allow for lower carbon emissions and pollution, increased energy and resource efficiency, and the preservation of biodiversity and ecosystem services (UNEP, 2023).

The role of the green economy, sustainable consumption and production, and resource efficiency in sustainable development goals (SDGs): Sustainable Consumption and Production aims to improve production processes and consumption practices to reduce resource consumption, waste generation, and emissions throughout the entire life cycle of processes and products, whereas Resource Efficiency refers to how resources are used to deliver value to society and aims to reduce the amount of resources required, as well as emissions and waste generated per unit of product or service. The Green Economy takes a macroeconomic approach to long-term economic growth, with a primary focus on investments, employment, and skills (UNEP, 2023).

These green investments must be enabled and supported by targeted public spending, legislative reforms, and changes in taxation and regulation. The Union Nations Environment Programmed advocates a development route that recognizes natural capital as a significant economic asset and a source of public benefits, particularly for disadvantaged people whose livelihoods rely on natural resources. The concept of green economy does not replace sustainable development, but rather places a renewed emphasis on the economy, investment, capital and infrastructure, jobs and skills, and beneficial social and environmental consequences throughout the African Union.

The green economy framework, which promotes sustainable consumption and production and resource efficiency, plays a critical role in advancing the Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 9 (Industry, Innovation, and Infrastructure). Sustainable development requires the application of advanced knowledge systems that optimize processes, reduce waste, and improve efficiency across sectors. The transition to a green economy hinges on the widespread adoption of renewable energy technologies, clean innovations, and energy-efficient practices, making the role of the knowledge economy indispensable (United Nations, 2021).

Renewable energy, especially solar and wind, presents significant opportunities for African countries to diversify their energy mix and reduce dependence on fossil fuels. However, the integration of these technologies requires effective ICT infrastructure to manage and optimize energy resources. The convergence of ICT and green energy is particularly important for Africa, where energy access remains a challenge and renewable energy is seen as a pathway to inclusive growth (Rogers et al., 2021). However, there is a significant gap in the literature on how ICT can drive green economic growth, particularly in the African context, where digital technologies and renewable energy are still emerging.

While the relationship between ICT, energy consumption, and economic growth has been explored in several studies, few have examined the intersection of ICT, renewable energy consumption, and green economic growth in the context of developing economies, particularly in Africa. Studies by Kumar et al. (2020) and Murshed et al. (2022) have highlighted the role of ICT in enhancing renewable energy adoption, but these studies are limited in their focus on the African continent, which faces unique challenges and opportunities in implementing both ICT and green technologies. Furthermore, existing research predominantly focuses on linear models that overlook the non-linear interactions between ICT adoption and renewable energy consumption.

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This study seeks to address these gaps by employing a non-linear ARDL (Autoregressive Distributed Lag) model to analyze the asymmetric effects of ICT and renewable energy on green growth in African countries.

To explore the policy implications for African governments and stakeholders aiming to foster sustainable development through ICT-enabled green growth. The central research question addressed in this study is: How do ICT adoption and renewable energy consumption jointly influence green economic growth in African countries?

This study makes several important contributions to the literature and practice: Novelty in Methodology: The use of a non-linear ARDL model is a key methodological contribution. This model allows for the examination of asymmetric relationships between ICT adoption, renewable energy consumption, and green growth, providing a deeper understanding of how these variables interact in both the short and long run. The study also introduces a squared ICT term to capture non-linear effects, a feature not commonly explored in existing literature.

By focusing on 40 African countries, this research provides region-specific insights that are crucial for understanding the dynamics of green growth in Africa. The study takes into account the continent's unique socio-economic challenges, including energy poverty, limited ICT infrastructure, and varying levels of investment in renewable energy.

This study reveals that ICT diffusion plays a crucial role in promoting sustainable economic growth in African countries, while financial development exhibits a negative relationship with growth due to structural inefficiencies in the financial sector. These findings emphasize the need for targeted policies to enhance digital infrastructure and address financial sector limitations, aligning with sustainable development goals in the region. These findings will offer valuable policy insights for African governments, energy policymakers, and international development organizations. Specifically, the study will inform strategies that encourage the adoption of ICT solutions to support renewable energy deployment, thereby enhancing green growth and contributing to the achievement of the SDGs in Africa.

The contribution to the Knowledge Economy, this research aligns with the core themes of the knowledge economy by demonstrating how knowledge creation, diffusion, and application—particularly through ICT innovations—can drive sustainable growth. The findings underscore the role of knowledge-driven technologies in facilitating the transition to green, low-carbon economies, which is essential for fostering economic development and environmental sustainability.

The paper is organized as follows: Section 2 presents the literature review. Section 3 describes the research methodology, including the data sources and the non-linear ARDL model employed. Section 4 presents the empirical results, discussing the short-term and long-term impacts of ICT and renewable energy consumption on green growth. In Section 5, we provide the conclusions and policy recommendations based on the findings of the study. By examining the synergies between ICT, renewable energy, and green growth, this study aims to contribute to both the literature on sustainable development and the field of the knowledge economy in the African context.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

The literature is replete with studies examining the relationship between green innovation, financial development, energy consumption, and green economic in African countries. Studies analysing this relationship abound in the literature.

Green growth, defined as economic progress achieved with minimal environmental harm, has gained significant traction as countries prioritize sustainable development in response to climate change and resource depletion (Zhang & Vigne, 2021). The pursuit of green growth emphasizes the integration of environmental sustainability with economic development, whereby economies strive to balance growth with reduced carbon footprints through clean energy and eco-friendly technologies (Song et al., 2022). Studies on green growth in African countries particularly focus on understanding how economic policies, technology, and environmental regulations influence sustainable progress (Adebayo et al., 2021; Sarkodie & Adams, 2018). The literature presents diverse perspectives on green growth, stressing the need for balanced frameworks to mitigate environmental impacts while fostering economic resilience (Chen et al., 2021).

2.1. Green Innovation and Green Economic Growth

The role of green innovation is pivotal in enabling green economic growth, as eco-friendly technologies and practices lower emissions, reduce waste, and improve resource efficiency (García-Sánchez et al., 2020; Balsalobre-Lorente et al., 2022). Green innovation encourages sustainable production processes and advances recycling, which aligns with the goals of green growth (Shahbaz et al., 2020). Furthermore, research suggests that innovations targeting environmental sustainability contribute to the long-term viability of industries, offering a pathway toward low-carbon growth (Zhao et al., 2021). However, the impact of green innovation on growth can be nonlinear, as indicated by studies employing advanced econometric models like the Generalized Method of Moments (GMM) to capture complex relationships between variables (Ulucak et al., 2021).

Green innovation has become increasingly vital in promoting green economic growth by driving the development of environmentally friendly technologies and practices that help reduce emissions, waste, and improve overall resource efficiency (Zhou et al., 2023; Chen et al., 2023). By integrating sustainable production processes and advancing recycling technologies, green innovation directly supports the goals of green growth, fostering a shift toward a more sustainable economy (Miao et al., 2023). Furthermore, research shows that green innovations contribute to the long-term economic sustainability of industries by facilitating the transition to low-carbon growth models (Wang et al., 2023).

Despite its importance, the relationship between green innovation and economic growth is not always linear. Recent studies employing advanced econometric methods, such as the Generalized Method of Moments (GMM), have highlighted the complexity of this relationship, revealing that the impact of green innovation on growth can vary depending on factors like technological maturity, economic development, and industry characteristics (Li et al., 2024). These findings suggest that while green innovation can spur growth, the effects may differ across different contexts and stages of development (Zhao et al., 2023; Saba et al.,2023). Indeed, this research can be further elaborated into this fundamental hypothesis which is: *Hypothesis (1),* as follow*:*

H1.1: There is a positive relationship between ICT and green growth.

H1.2: The relationship between ICT and green growth is nonlinear.

2.2. Renewable Energy Consumption and Green Growth

Renewable energy consumption is a cornerstone of green economic growth, as it reduces reliance on fossil fuels, mitigates greenhouse gas emissions, and promotes environmental sustainability (Zhou et al., 2024; Liu et al., 2024). The transition to renewable energy sources is essential for achieving long-term sustainable development goals, as it aligns economic growth with ecological preservation (Zhang et al., 2024). However, the relationship between renewable energy consumption and green growth is not always straightforward and may exhibit nonlinear characteristics, such as U-shaped or inverted U-shaped patterns, depending on various contextual factors.

For a Positive Mechanisms, renewable energy consumption directly reduces carbon emissions and environmental degradation, contributing to green growth by fostering cleaner production processes and sustainable resource use (Singh et al., 2023). This positive effect is particularly pronounced in countries with high initial reliance on fossil fuels, where the shift to renewables yields significant environmental and economic dividends.

Moreover, investments in renewable energy infrastructure can stimulate economic growth by creating jobs, enhancing energy security, and improving productivity (Zhang et al., 2024). For instance, the development of solar and wind energy projects often leads to technological spillovers and innovation, which further drive green growth.

In developing nations, renewable energy projects can address socio-economic challenges by providing affordable and reliable energy access, thereby improving living standards and reducing poverty (Liu et al., 2024).

For negative Mechanisms, the adoption of renewable energy technologies often requires substantial upfront investments and infrastructure development, which can strain financial resources and slow economic growth in the short term (Wang et al., 2023). This may lead to an initial negative impact on green growth, particularly in low-income countries with limited financial and technical capacity.

Furthermore, inefficiencies in renewable energy systems, coupled with inadequate regulatory frameworks, can hinder the optimal utilization of clean energy resources, thereby limiting their contribution to green growth (Chien et al., 2022).

Also, the shift from fossil fuels to renewables may involve transitional costs, such as stranded assets in the fossil fuel industry and temporary disruptions in energy supply, which could negatively affect economic performance in the short run (Ozcan & Ozturk, 2019).

The interplay between these positive and negative mechanisms suggests that the relationship between renewable energy consumption and green growth may not be linear. For instance, in the early stages of renewable energy adoption, the high costs and infrastructure challenges may outweigh the benefits, resulting in a negative or negligible impact on green growth. However, as technological maturity improves and economies of scale are achieved, the positive effects of renewable energy consumption may dominate, leading to a U-shaped relationship. Conversely, in some cases, an inverted U-shaped relationship may emerge if diminishing returns set in after a certain threshold of renewable energy adoption, where further increases in renewable energy consumption yield progressively smaller gains in green growth.

Based on this discussion, we refine Hypothesis 2 as follows:

H2: The relationship between renewable energy consumption and green growth is nonlinear, potentially exhibiting a U-shaped or inverted U-shaped pattern due to the interplay of positive and negative mechanisms.

2.3. ICT and Renewable Energy Interaction Effect on Green Growth

The intersection of ICT and renewable energy is increasingly recognized as a critical factor in driving green growth. Advances in digital technologies enable better energy management and optimization, which enhances the efficiency of renewable energy systems (Chien et al., 2022). The integration of ICT in the energy sector supports resource conservation efforts, reduces emissions, and promotes green growth, particularly when coupled with regulatory frameworks that encourage environmental sustainability (Wang et al., 2023).

The convergence of ICT and renewable energy is increasingly acknowledged as a key driver of green growth. Recent advancements in digital technologies have significantly improved energy management and system optimization, leading to higher efficiency in renewable energy utilization (Li et al., 2024).

The integration of ICT within the energy sector not only aids in resource conservation and emission reductions but also fosters green growth, especially when supported by robust regulatory frameworks that promote sustainability and environmental responsibility (Chen et al., 2024).

Additionally, the use of ICT tools, such as smart grids and energy storage systems, plays a crucial role in enhancing the flexibility and resilience of renewable energy infrastructure, paving the way for more sustainable energy solutions (Zhao et al., 2023). Really, this research can be expanded upon by building on the core of *Hypothesis 3.*

H3: The interaction between renewable energy consumption and ICT has a positive effect on green growth.

2.4. Financial Development as a Driver of Green Growth

Financial development is another critical component for green growth, as it provides the necessary capital for eco-friendly investments and technological advancements (Das et al.,2018; Pradhan et al., 2021). Theoretically, well-developed financial markets facilitate the efficient allocation of resources toward sustainable projects, driving economic growth while supporting environmental goals (Chishti & Mohsin, 2022). However, excessive speculation or misallocation of financial resources may reduce the effectiveness of financial development as a tool for green growth (Ozcan & Ozturk, 2019).

Financial development is a vital driver of green growth, as it provides the essential funding for environmentally sustainable investments and technological innovations (Zhao et al., 2023). Well-functioning financial markets enable the efficient allocation of capital to green projects, fostering economic development while simultaneously advancing environmental objectives (Wang & Zhang, 2024). However, challenges arise when financial markets are plagued by speculation or the misallocation of resources, which can undermine their potential to contribute to green growth (Khan et al., 2023). To ensure that financial development supports sustainability, it is crucial to establish robust regulatory frameworks and foster greater transparency in financial markets (Liu & Zhang, 2024). Certainly, this research can be expanded further by building on the foundational of *Hypothesis 4.*

H4: The effect of financial development on green growth is positive.

The hypothesis suggests that financial development plays a crucial role in fostering green growth by providing the capital necessary for eco-friendly investments and technological advancements. Well-developed financial markets can effectively allocate resources to sustainable projects, driving both economic growth and environmental goals. However, the effectiveness of financial development for green growth can be undermined by issues such as excessive speculation or misallocation of resources, highlighting the need for proper regulatory frameworks and transparency in financial markets.

3. EMPIRICAL METHODOLOGY

3.1. Model specification

In this study, we carefully selected parameters that directly impact green economic growth within African economies, focusing on Information and Communication Technology (ICT) adoption and renewable energy consumption. ICT was included as it facilitates resource efficiency and supports innovation in energy management, aligning with sustainable growth objectives (Zhao et al., 2023). Renewable energy consumption is another critical factor, given Its direct role in reducing emissions and dependency on fossil fuels (Chien & Sadiq, 2023). Additional control variables were chosen to account for economic and environmental factors known to influence green growth, such as GDP per capita (Grossman & Krueger, 1995), trade openness (Shahbaz et al., 2013), and urbanization rates (Hossain, 2011). These variables are widely recognized in the literature as key determinants of green economic growth, as they influence energy consumption patterns, technological diffusion, and environmental sustainability. The selection of these parameters is based on both theoretical frameworks and empirical evidence from studies on green economic growth in developing economies (Sadorsky, 2010; Omri, 2013). Figure 1 presents the empirical methodology of our study.

Thus, with reference to the specification of Yu et al. (2022) and Dahmani et al. (2023), the model can be written as follow:

$$EAMFP_{it} = \beta_0 + \beta_1 Act_{it} + \beta_2 GFCF_{it} + \beta_3 FDI_{it} + \beta_4 REC_{it} + \beta_5 CO2_{it} + \beta_6 DCPS_{it} + \beta_6 ICTET_{it} + \varepsilon_{it} \quad (1)$$

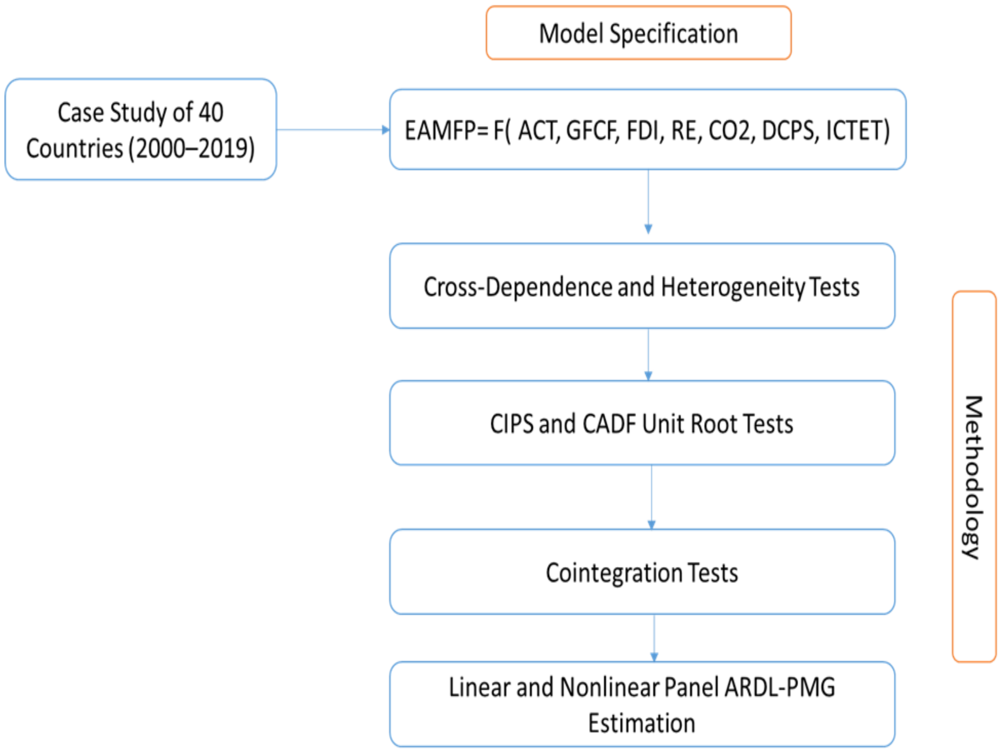

Figure 1. Methodology Framework.

We utilized the Nonlinear Autoregressive Distributed Lag (NARDL) model, which allows for the examination of both short- and long-term relationships between variables and the detection of asymmetrical effects. This model is particularly suited for our study as it can capture the nonlinear relationship between ICT, renewable energy consumption, and green growth, essential for understanding dynamic interactions in an emerging economy context (Shin et al., 2014).

$$lEAMFP_{it} = \beta_0 + \beta_1 lAct_{it} + \beta_2 lGFCF_{it} + \beta_3 lFDI_{it} + \beta_4 lREC_{it} + \beta_5 lCO2_{it} + \beta_6 lDCPS_{it} + \beta_6 lICTET^{+}{}_{it} + \beta_7 lICTET^{-}{}_{it} + \eta_i + \varepsilon_{it} \quad (2)$$

where $lICTET^{+}$ and $lICTET^{-}$ represent the decomposed oil prices into partial sums of positive and negative changes, respectively.

The NARDL model was chosen over conventional linear models due to its flexibility in handling data series with different integration orders and its ability to capture asymmetric effects, which are significant when analyzing responses to positive and negative shocks in ICT adoption and renewable energy consumption. Given the unique context of African economies, we introduced an additional squared term for ICT to account for potential diminishing or increasing returns of ICT investments on green growth. This adaptation allows for a nuanced understanding of ICT's role, particularly relevant in resource-limited contexts where technological impact may vary based on infrastructure maturity and access levels.

In this study, the nonlinear ARDL method is employed in a panel data form. This econometric approach involves a nonlinear representation of dynamic heterogeneous panel (ARDL) estimators, specifically the Pooled Mean Group (PMG) method (Pesaran et al., 1999), as utilized by Nusair (2019) and Salisu and Isah (2017). The PMG method allows short-run coefficients, the speed of adjustment, and error variances to vary across panels while constraining the long-run coefficients to be uniform across groups. Additionally, the PMG produces consistent estimates of the mean of the short-run coefficients by averaging the individual unit coefficients. The choice of the nonlinear panel ARDL method for this study is motivated by several factors: it allows for the combination of I(0) and I(1) variables, enables the estimation of nonlinear asymmetric relationships by decomposing the variable of interest into partial sums of positive and negative changes, and captures heterogeneity effects across panels.

The following equation (3) is specified to represent the nonlinear asymmetric model, incorporating the decomposed ICT into partial sums of positive and negative changes, as established by Shin, Yu, and Greenwood-Nimmo (2014).

$$lEAMFP_{it} = \gamma_i lEAMFP_{i,t-1} + \delta_1 lAct_{it} + \delta_2 lGFCF_{it} + \delta_3 lFDI_{it} + \delta_4 lREC_{it} + \delta_5 lCO2_{it} + \delta_6 lDCPS_{it} +$$

$$\delta_6 lICTET^{+}_{it} + \delta_7 lICTET^{-}_{it} + \sum_{j=1}^{\rho=1} Y_{ij} \Delta\, lEAMFP_{i,t-1} + \beta_{ij} \Delta lAct_{i,t-1} + \beta_{ij} \Delta lGFCF_{i,t-1} + \beta_{ij} \Delta lFDI_{i,t-1} + \beta_{ij} \Delta lREC_{i,t-1} + \beta_{ij} \Delta lCO2_{i,t-1} \sum_{j=1}^{\rho=1} \beta_{ij} \Delta\, lEAMFP_{i,t-1} + \eta_i + \varepsilon_{it} \quad (3)$$

where, δ is the long-run coefficient of the independent variables, and γ is the speed of adjustment parameter towards the long-run equilibrium. η\etaη represents the fixed effect, and ε is the error term. The indices *i* and *t* denote the country and time, respectively. It is assumed that the error term ε in the PMG framework is distributed independently across *i* and *t* with zero mean and constant variance. The error term is also assumed to be distributed independently of the regressors. Additionally, to capture the long-run relationship between the dependent and independent variables, it is assumed that if the speed of adjustment parameter is less than <0 ($\gamma < 0$) for all *i*, then panel co-integration is established as follows:

$$lEAMFP_{it} = \varphi_1 lAct_{it} + \varphi_2 lGFCF_{it} + \varphi_3 lFDI_{it} + \varphi_4 lREC_{it} + \varphi_5 lCO2_{it} + \varphi_6 lDCPS_{it} + \varphi_7 lICTET^{+}_{it} + \varphi_7 lICTET^{-}_{it} + \eta_i + \varepsilon_{it}$$

where, $\varphi$is the long run coefficient of each variable.

3.2. Data and Preliminary Analysis

Our sample is made up of a group of 40 countries member in Africa region such as Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Congo (The Republic), Cote d'Ivoire, Equatorial Guinea, Ethiopia, Egypt, Gabon, Gambia, Ghana, Guinea, Guinea- Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Niger, Nigeria, Rwanda, , Senegal, Sierra Leone, South Africa, Sudan, Tanzania, Tunisia, and Zambia for the period between 2000 and 2019.

Before the analysis of preliminary tests such as homogeneity tests, Cross-Dependence tests, unit root and cointegration tests. We present the relative descriptive statistics of the different variables that have been log-transformed. All the variables are summarized in Table 1.

Table 1. Definition of variables and descriptive statistical analysis results

Variables	Definition	Obs.	Mean	Std. Dev.	Min.	Max.	Source
LnEAMFP	Environmental Adjusted Multifactor Productivity	800	1.346	0.830	-3.387	4.463	OCDE
LnAct	The percentage of the labor force	800	4.145	0.215	3.692	4.481	WDI
LnGFCF	The ratio shows the proportion of GDP invested in fixed assets	800	3.006	0.420	0.693	4.394	WDI
LnFDI	The total amount of foreign direct investment received by a country during a specific period, as a percentage of GDP	800	0.455	2.147	-16.118	3.684	WDI
LnREC	Energy use(kg of oil equivalent per capita)	800	4.101	1.769	-2.813	11.177	WDI
LnCO2	CO2 emissions (kt)	800	8.307	1.968	4.341	13.012	EIA
LnDCPS	Domestic credit to private sector by banks (%GDP))	800	2.695	1.094	-16.118	4.959	WDI
LnICTET	The ratio of ICT exports to ICT technology imports	800	1.228	0.586	-5.177	2.547	WDI

Note: Variables are log-transformed.

For the variable EAMFP, the 800 observations show an overall mean of 1.346 with a standard deviation equal to 0.830. In addition, both the normality test of Jarque and Bera (1987) test and the Born & Breitung (2016) autocorrelation test indicate a probability of less than 1%. The REC variable had an overall mean of 4.101 with a standard deviation of 1.769. For the DCPS variable, the 800 observations show an overall mean of 1.228 with a standard deviation equal to 0.586 and all the values are included between -16 and 5. The ICT variable had an overall mean of 4.101 with a standard deviation of 1.769. Moreover, both the normality test and the Born & Breitung (2016) autocorrelation test indicate a probability of less than 1%. The null hypothesis of these two tests is therefore rejected, confirming the presence of a second-order autocorrelation problem.

4. RESULTS AND DISCUSSIONS

4.1. Results

The next step after the descriptive analysis consists to examine the existence of a dependence relationship between individuals in the model. The examination of cross-sectional dependence (CD) in the panel data is of utmost important, because the presence might produce biased and inconsistent empirical results (Phillips & Sul, 2003). In fact, having a high degree of dependency between countries does not mean that a country uses largely the same dynamics in the development process. It may be that each country has its specific characteristics.

According to Breitung (2005), it is impossible to capture the heterogeneity that might occur given country-specific characteristics under the assumption of parameter homogeneity (Wolde-Rufael, 2014). In this context, we examine the existence of the dependence relationship by several tests such as Friedman (1937), Breusch Pagan (1980), Frees (1995 & 2004), Pesaran (2004, 2006 & 2015). The H_0 hypothesis created for the tests states that there is no cross-section dependency, while H_1 hypothesis states that there is a cross-section dependency. According to the test results, if H_0 hypothesis is accepted, the analysis should be continued with the first-generation panel unit root tests, and if H_1 hypothesis is accepted, the analysis should be continued with the second-generation panel unit root tests (Baltagi & Baltagi 2008).

The choice of model estimation method using panel data is based on determining the nature of the slope. To test for uniformity of slopes, we use the test of Pesaran and Yamagata (2008), which is based on the dispersion of each individually weighted slope. Monte Carlo simulations show that the test is suitable for small sample sizes and for dynamic and unbalanced panel data.

We tested the slope homogeneity assumption using the Pesaran and Yamagata (2008) test. Table 2 shows that in all cases the null hypothesis of homogeneity of slopes is rejected because the probability value is less than 0.01. Therefore, we need to consider the presence of heterogeneity in the panel data and conclude that the model coefficients are heterogeneous and the slopes vary across countries. Therefore, we need to use heterogeneous panel technology.

Table 2. Slope Homogeneity Test (Pesaran and Yamagata, 2008)

Pesaran and Yamagata (2008)		
	Value	Probability
Delta	2.976***	0.003
delta adjusted	4.012 ***	0.000

Table 3 presents the results of Friedman (1937), Frees (1995 & 2004) and Pesaran (2015) cross-correlation tests and shows that cross-sectional correlation exists for all variables in the panel data. In other words, there is an element of dependence between countries, meaning that a shock to one country can have ripple effects that ripple out to other countries. This suggests the need for a second generation unit root test.

Table 3. Tests for weak cross-sectional dependence.

Tests	**Value**	**Probability**	**Decision**
Friedman (1937)	60.414	0.010	Dependence
Frees (1995 & 2004)	0.769	0.000	Dependence
Pesaran (2015)	5.436	0.000	Dependence

Table 4 shows the results of CIPS and CADF stage tests and first differences. The results show that some variables are stationary in panel A, i.e. I(0), and the other variables are stationary in first differences, i.e. I(1).

Table 4. Results of panel unit root tests.

	InEAMFP	**InAct**	**InGFCF**	**InFDI**	**InREC**	**InCO2**	**InDCPS**	**InICTET**
Cross-Sectionally Augmented IPS (CIPS)								
	Panel A: In level							
Without T	-3.556*	-1.125*	-1.944	-2.981 *	-1.976	-2.325	-2.325	-2.726 ***
With T	-4.019*	-1.352*	-2.260	-3.831***	-2.620	-2.613	-2.786***	-2.980
Decision	NS	NS	NS	S	NS	NS	NS	S
	Panel B: In first difference							
Without T	-5.375***	-1.586	-3.839***	-5.500***	-3.884***	-4.235***	-4.235***	-4.967***
With T	-5.404**	-1.978	-3.993***	-5.505***	-4.031***	-4.365***	-4.347***	-5.052***
Decision	S	NS	S	S	S	S	S	S
Cross-Sectionally Augmented Dickey-Fuller (CADF)								
	Panel A: In level							
Without T	-2.113***	-1.183	-2.181***	-2.668***	-2.277***	-1.233	-0.498	-2.051***
With T	-2.461	-2.045	-1.971	-2.507	-2.358	-1.876	-0.809	-2.182
Decision	NS	NS	NS	S	S	NS	NS	S
	Panel B: In first difference							
Without T	-2.883***	-1.331	-1.810	-2.327	-2.225	-2.255***	-2.097***	-2.524***
With T	-2.774***	-2.078	-1.900	-2.146***	-2.416	-2.168***	-2.071	-2.709***
Decision	S	NS	NS	S	NS	S	S	S

Table 5 displays the outcomes of the Persyn and Westerlund (2008) cointegration test conducted on data from 35 African countries across all variables. This method is particularly advantageous as it effectively handles situations with varying slope coefficients and interdependencies among individual panel data. The null hypothesis posits no long-term cointegration among the variables, while the alternative suggests the opposite.

The Persyn and Westerlund (2008) test results reject the null hypothesis of non-cointegration at the panel level rather than at the individual country level. Concurrently, Pedroni's (2004) test results (presented in Table 5) reject the null hypothesis of no cointegration for six out of seven statistics. Consequently, it becomes imperative to estimate the long-term equilibrium relationships between these variables.

Table 5. Results of cointegration tests.

	Tests	**Value**		**p-value**	**Decision**
	Kao (1999)	-1.440		0.000	Cointegration
First generation	Pedroni (2004)	-15.678		0.000	Cointegration
	Westerlund (2007)	-1.866		0.031	Cointegration
	Persyn and Westerlund (2008)	Value	Z-value	p-value	
	G_t	-2.649	-2.198	0.014	Cointegration
Second generation	G_a	--9.827	2.032	0.979	Cointegration
	P_t	-16.645	-3.756	0.001	Cointegration
	P_a	-11.829	-2.987	0.000	Cointegration

Based on these results, to examine the symmetry and asymmetry relationship between renewable energy consumption, financial development, ICT diffusion, and green growth in African countries., the empirical analysis employs the NARDL-PMG approach. Coefficient estimates for these models, both in the short and long run, are presented in Table 6.

Table 6. Linear and nonlinear panel ARDL (PMG) results.

	Model 1: without Asymmetry Pooled Mean group (PMG)	Model 2: with Asymmetry Pooled Mean group (PMG)
Long run coefficients		
lICTET	0.072 (0.065)	–
lICTET$^+$	–	0.125**(0.063)
lICTET$^-$	–	0.190** (0.069)
lACT	1.197 (0.812)	2.284**(0.767)
lGFCF	0.263 (0.124)	0.504 **(0.108)
lFDI	0.057 (0.018)	0.054 **(0.019)
REC	-0.522 (0.167)	0.103 (0.105)
lCO2	-0.057 (0.087)	-0.016 (0.084)
lDCPS	0.058 (0.046)	-0.042 (0.048)
Short run coefficients		
∆*lICTET*	-0.081 (0.208)	–
∆*lICTET*$^+$	–	-0.058 (0.349)
∆*lICTET*$^-$	–	0.141 (0.353)
∆*lACT*	-92.694 (92.636)	-149.059 (118.221)
∆*lGFCF*	-0.801 (0.430)	-0.668 (0.473)
∆*lFDI*	0.082 (0.049)	0.067 (0.051)
∆*REC*	3.145 (9.539	0.777 (10.831)
∆*lCO2*	-0.840 (1.176)	-0.502 (1.146)
∆*DCPS*	-0.429 (0.7407)	-0.320 (0.201)
Convergence Coefficient	0.890[a] (0.210)	0.879 (0.063)
Wald test	–	7.98**
Log likelihood	-434.572	-389.300
No of countries	40	40
No of obs.	760	760

Note: Numbers in parentheses are asymptotic standard errors except for Wald tests. AIC criterion is used to choose the lag order. *,** and ***denote significance level at 1%, 5%and 10% respectively.

The PMG (symmetric and asymmetric) results were computed and then results were subjected to Wald test for making preference of the appropriate method to take. The non-rejection of the null is signifying the presence of long run homogeneity (PMG is appropriate). In this study, the Wald test result clearly indicates the PMG is the appropriate estimator as the null hypothesis is not rejected as displayed in Table 6. As such, the results from the preferred estimate, PMG are going to be explained.

According to the table above, the results of the linear and nonlinear ARDL models for both the short term (upper rows) and long term (lower rows) relationships. we observe that the positive and significant effect of the error term (-0.12, p=0.000) in the symmetric and asymmetric estimations suggest a robust relationship between the variables studied, despite the random disturbances.

Additionally, the symmetric in long-run results based on the NARDL estimator show that LICT is positively and significantly related to gross fixed capital formation, energy consumption, and ICT. Specifically, a 1% increase in LACT, LGFCF, LFDI, and LDCPS stimulates LGDP_PC by 0.072%, 1.197%, 0.263%, 0.057%, and0.058%, respectively.

The empirical results also reveal that the impacts of renewable energy and CO2 on green economic growth in the African region are -0.522 % and -0.057 %, respectively. This suggests significant policy implications, indicating that African economies should focus on the energy sector to ensure energy security and leverage the negative impact on long-term growth. Investments should be primarily directed towards renewable energies, assessing the effects of phasing out fossil fuels in sectors such as electricity, transport, and industry. Several countries face severe challenges due to a lack of investment and continue to be heavily dependent on petroleum resources. Successful development of renewable energies requires a stable political, regulatory, and legal environment to attract foreign and domestic investment, support mechanisms, reduction of fossil fuel subsidies, and incentives for simpler administrative processes and efficient energy use.

In contrast, the estimated coefficient for financial development, in asymmetric approach, is negative and significant at the 1% level, indicating that a 1% improvement in financial development reduces InEAMFP by 0.042%. This finding is consistent with previous studies by Adeniyi et al. (2015), Barajas et al. (2011), Cheng et al. (2021), Kenza and Salah Eddine (2016), Samargandi et al. (2015), and Sassi and Goaied (2013).

Furthermore, financial development is negatively related to economic growth, possibly due to weaknesses in the financial sector, lack of competition in banking systems, misallocation of financial resources, macroeconomic volatility, financial crises, or nonlinear relationships (Ben Abdallah et al.,2024). Our estimation results also show a positive and statistically significant influence of ICT on GDP, consistent with the findings of Cheng et al. (2021), Das et al. (2018), Fernandez-Portillo et al. (2020), Pradhan et al. (2017), and Sassi and Goaied (2013), who recognized the positive effects of ICT diffusion on economic growth. If ICTs are considered general-purpose technologies (Helpman and Trajtenberg, 1998), African countries will need to invest in ICT to achieve their full potential for supporting economic growth and mitigating the negative effects of financial development on economic growth. Financial sector developments need to be reinforced by ICT infrastructure, greater Internet penetration, and further integration of electronic finance policies. ICT will also play a crucial role in promoting renewable energy, improving energy efficiency, combating climate change, and facilitating the energy transition by advancing energy research to reduce production, logistics, and maintenance costs.

It is important to note that the short-run results of the NARDL model are similar in both magnitude and sign to the long-run results. For the 40 African countries studied, an economic interpretation of the impact ICT on green growth is as follows: The adoption and diffusion of ICT promotes sustainable economic growth by improving energy efficiency and reducing operational costs. ICT enable better management of natural resources, facilitate innovation in green technologies and optimize industrial processes, thus contributing to a greener economy. For example, the use of ICT in the management of electricity networks can improve the integration of renewable energies, reduce energy losses and stabilize networks.

In addition, ICT play a crucial role in environmental awareness and education, informing people about sustainable practices and encouraging the adoption of environmentally-friendly behavior. They also facilitate access to markets and finance for green businesses, stimulating innovation and job creation in the clean technology sector.

In summary, the positive impact of ICT on green growth in African countries can be attributed to their ability to improve efficiency, foster innovation and encourage the adoption of green technologies. So, we can have referred and accept all the hypotheses.

To ensure the robustness of our findings, we will conduct additional tests following the methodologies proposed by Haans et al. (2015) and Lind and Mehlum (2010) to evaluate the presence of U-shaped or inverted U-shaped relationships between key variables. These methods will allow us to rigorously test the nonlinear dynamics, identify turning points, and provide visual representations of these relationships, thereby strengthening the validity and reliability of our results. This approach will also address the reviewer's concerns by offering a more comprehensive and transparent analysis of the underlying mechanisms driving green growth in African countries.

In our regression analyses, the squared term for related variety consistently shows a positive coefficient. However, this finding alone does not conclusively demonstrate the presence of a U-shaped relationship, as a statistically significant quadratic term can also occur within a monotonic range (Lind & Mehlum, 2010). To address this, we follow the methodologies outlined by Lind and Mehlum (2010) and Haans et al. (2016). Specifically, we first determine the extreme point of the potential U-shaped curve and then evaluate the slopes on both sides of this point. The outcomes of these tests are presented in Table 7.

Table 7. U-shaped test.

	Lower Bound	Upper Bound
Interval	-5.177	2.547
Slope	-0.141	0.085
t-value	-0.544	0.863
P > 1	0.293	0.194

Note: the extreme point is -0.368; overall test of presence of U-shaped: t-value=0.54; $|p > 1| = 0.29$

The interval of ICT is [−5.177, 2.257] with the extreme point −0.368. In the left interval [−5.177, −0.368], the slope is −0.141 and statistically significant ($p < 0.1$); in the right interval [−0.368, 2.257], the slope is 0.085 with statistical significance ($p < 0.1$). These results suggest a U-shaped relationship, as the slope is negative and significant on the left side of the extreme point and positive and significant on the right side. Figure 2 visually represents this U-shaped relationship, further supporting the interpretation. The analysis confirms the presence of a U-shaped relationship between the variables under consideration.

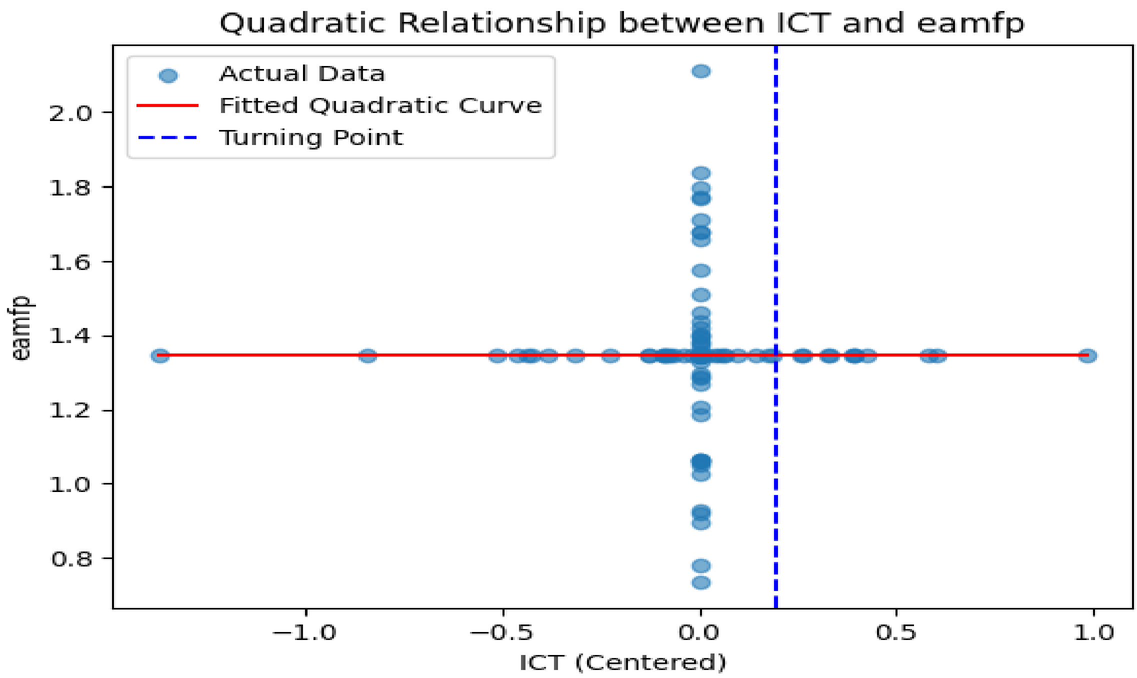

Figure 2. The U-shaped relationship between ICT and EAMFP.

The combination of a statistically significant negative slope on the left, a statistically significant positive slope on the right, and the visual representation in the figure strongly supports the conclusion that a U-shaped relationship exists. This finding confirms ***H2***: The relationship between renewable energy consumption and green growth is nonlinear, potentially exhibiting a U-shaped or inverted U-shaped pattern due to the interplay of positive and negative mechanisms.

4.3. Discussions

This study investigates the relationships between ICT diffusion, financial development, renewable energy consumption, and economic growth in African countries, employing symmetric and asymmetric PMG and NARDL models to capture both short- and long-term effects. The findings provide new insights into how these factors interact, with significant implications for green economic growth policies in African economies.

In expanding the discussion with comparisons to Huang et al. (2024) and Yahyaoui (2024), the results here further substantiate ICT's positive influence on sustainable growth. Huang et al. (2024) similarly found that ICT infrastructure significantly boosted energy efficiency and contributed to green growth through cost reductions and optimized resource allocation. This finding supports the interpretation that ICT functions as a general-purpose technology, enabling structural and economic efficiencies in resource-constrained economies, consistent with the theoretical framework of Helpman and Trajtenberg (1998). Furthermore, Yahyaoui

(2024) emphasized ICT's potential to mitigate the negative impacts of financial sector volatility, reinforcing the argument that ICT plays a stabilizing role in fostering sustainable growth amidst financial instability.

The negative association between financial development and economic growth, observed here in line with Samargandi et al. (2015), finds additional support in the findings of Huang et al. (2024), who highlighted the adverse effects of weak financial structures in emerging economies. Their study indicates that financial sector expansion without sufficient regulation or inclusivity can lead to misallocation of resources and increased exposure to economic shocks. This aligns with our conclusions that African financial systems need restructuring to enhance efficiency and reduce vulnerability. Yahyaoui (2024) also noted that limited financial inclusivity and high dependency on foreign capital contribute to economic instability, echoing concerns raised in Adeniyi et al. (2015) regarding the challenges facing African financial institutions.

This comparative analysis enriches the understanding of ICT and financial sector dynamics in the African context, highlighting both the potential and the challenges associated with achieving green growth. These findings underscore the need for policy measures to strengthen digital infrastructure, enhance financial inclusivity, and support targeted financial reforms that foster sustainable economic progress across the region.

The observed positive influence of renewable energy consumption on green growth also reinforces prior findings that emphasize the importance of renewable investments (Dahmani et al., 2021). The negative effect of CO_2 emissions on economic growth suggests an urgent need for a clean energy transition, consistent with global studies advocating for increased renewable energy adoption to balance economic and environmental priorities (Cheng et al., 2021; UNEP, 2023).

These findings contribute to the existing literature by demonstrating that ICT and renewable energy adoption are pivotal to achieving sustainable growth in African economies. ICT plays a crucial role in optimizing renewable energy consumption by enabling smart grid systems, improving energy efficiency, and supporting the integration of renewable energy sources into national power grids. Through advanced data analytics and automation, ICT enhances the effectiveness of renewable energy deployment, reducing energy waste and promoting a more sustainable energy transition. From a theoretical perspective, this study expands on the knowledge economy literature by showing that ICT not only drives economic growth but also plays a critical role in renewable energy adoption. ICT-driven innovations, such as real-time energy monitoring and automated grid balancing, contribute to the efficient deployment of renewable energy, reducing energy losses and enhancing sustainability. This study also builds on the environmental Kuznets curve theory, providing evidence that ICT investments, alongside renewable energy integration, can foster economic growth while mitigating environmental degradation (Grossman & Krueger, 1991).

The results suggest several policy and managerial implications for African economies. First, the positive influence of ICT on green growth implies that policymakers should prioritize ICT investment to drive sustainable economic growth. This could involve expanding digital infrastructure, enhancing digital literacy, and increasing access to digital technologies, particularly in underserved rural areas, to bridge the digital divide. Strengthening digital infrastructure can support more efficient resource use, environmental awareness, and green business innovation, as recommended by prior research (Fernandez-Portillo et al., 2020).

The positive role of renewable energy on growth further indicates that governments should continue to invest in renewable energy projects and create regulatory frameworks that encourage private investment. Measures could include reducing subsidies for fossil fuels, simplifying administrative processes, and providing incentives for renewable energy development. To enhance the attractiveness of the renewable sector, African policymakers need to ensure a stable political and regulatory environment, which is essential for attracting domestic and foreign investments.

Regarding financial development, the study's findings suggest the need for reforms to create a more inclusive and stable financial sector. By enhancing competition, transparency, and efficiency within financial institutions, African economies could mitigate the negative impact observed in this study. Initiatives to promote financial inclusion, such as mobile banking, fintech, and microfinance programs, could provide access to financial services for underserved populations, fostering inclusive growth and supporting green investments (Cheng et al., 2021).

Based on the results obtained, all hypotheses of this study were accepted. The findings provide strong empirical support for the positive relationship between ICT diffusion and green economic growth, suggesting that digital technologies contribute to economic expansion while fostering environmental sustainability. This aligns with previous studies indicating that ICT enhances productivity and facilitates resource efficiency in various sectors.

Moreover, our results highlight the negative impact of financial development on economic growth in African economies, which may be attributed to inefficient allocation of financial resources, weak regulatory frameworks, or the dominance of short-term speculative activities. This finding suggests the need for structural reforms to ensure that financial development translates into productive investments that support sustainable economic growth.

Additionally, the positive effect of renewable energy consumption on green growth underscores the role of clean energy in fostering economic resilience and environmental protection. The significant negative impact of CO_2 emissions on economic performance further reinforces the urgency of integrating sustainable energy policies and carbon reduction strategies. These insights validate our proposed theoretical framework and emphasize the crucial role of ICT and renewable energy in driving long-term sustainable development in African economies.

This study has introduced an expanded perspective on the research problem by highlighting the critical role of ICT as an enabler of green growth through resource efficiency, environmental education, and economic diversification in African countries. New ways of thinking about the issue could involve exploring the synergistic role of digital innovations, such as the Internet of Things (IoT) and artificial intelligence (AI), in enhancing green technology deployment and optimizing energy networks. This approach could foster a more comprehensive understanding of how digital transformation can accelerate the energy transition and mitigate environmental impacts in African economies.

5. CONCLUSION

This study examined the dynamic relationship between ICT diffusion, financial development, renewable energy consumption, and green economic growth in African countries. Building on the foundational work of Cheng et al. (2021) and Dahmani et al. (2021), our research contributes to the growing literature by focusing on the African context, where unique challenges and opportunities exist for green growth. Through this analysis, three main findings emerged that hold significant implications for theory, policy, and future research.

5.1. Managerial and Policy Implications

From a policy standpoint, our study provides actionable insights for African policymakers. First, the positive impact of renewable energy on green growth suggests that African nations should prioritize renewable energy initiatives. Policymakers should consider incentivizing investments in clean energy infrastructure, supporting research and development in sustainable energy technologies, and implementing regulatory frameworks that promote renewable energy adoption. Such initiatives will help not only in achieving energy security but also in reducing greenhouse gas emissions and creating sustainable jobs within the green economy.

Second, the negative relationship between financial development and economic growth in Africa suggests that improving financial sector resilience is essential. Addressing macroeconomic volatility and promoting regulatory reforms can enhance the financial system's stability and inclusivity. Policymakers could focus on reducing systemic risks, encouraging financial inclusion, and creating safeguards to prevent financial crises that disrupt economic progress. Additionally, fostering financial innovation, such as green financing instruments and sustainable investment funds, could help channel capital towards environmentally beneficial projects.

Third, the significant positive impact of ICT on green growth highlights the need for continued digital investment. Governments and organizations should prioritize expanding digital infrastructure, closing the digital divide, and enhancing digital literacy across the population. Equipping the workforce with relevant e-skills is crucial, as it will empower citizens to participate in and benefit from the digital economy. Additionally, firms should be encouraged to adopt advanced digital technologies and modern organizational practices, positioning ICT as a critical lever for sustainable economic transformation.

5.2. Addressing the Research Gap and Contribution

While existing literature explores the roles of ICT, financial development, and renewable energy in economic growth, research on the intersection of these variables in the context of green growth in Africa remains limited. This study fills this gap by providing empirical evidence on how these variables interact within African economies, a region facing unique environmental and economic challenges. By focusing on African countries, this research sheds light on the specific conditions, such as financial sector weaknesses and infrastructural gaps, that influence green growth outcomes in emerging economies. The study's findings offer a tailored approach to policy formulation for African nations, demonstrating how targeted investments in ICT and renewable energy, coupled with strategic financial reforms, can contribute to sustainable economic growth.

5.3. Findings and Suggestions for Future Research

Our findings underscore the pivotal role of renewable energy and ICT in driving green economic growth, particularly in economies striving to reduce their environmental impact while fostering sustainable development. This study highlights a unique relationship between financial development and green growth in Africa, which, unlike many regions, shows a negative association due to structural and financial instability. This result challenges the conventional understanding of financial development as a universally positive driver of economic growth, suggesting instead a nuanced relationship where financial systems' characteristics and maturity levels play a critical role in outcomes.

By introducing the Nonlinear ARDL (NARDL) model to capture asymmetrical effects, this study also contributes methodologically to the literature, enabling a deeper exploration of non-linear dynamics within ICT and renewable energy impacts on green growth. These insights add depth to green growth theory, emphasizing that structural economic factors and technology diffusion interact in complex ways that vary by region and developmental stage.

Future research could expand upon this study by exploring additional variables that may influence green growth in African economies, such as human capital development, foreign direct investment, and climate resilience policies. Additionally, longitudinal studies examining post-2020 data would provide insights into how global events, such as the COVID-19 pandemic and the Russia-Ukraine conflict, impact the dynamics of green growth in Africa. Future research could also investigate sector-specific applications of ICT and renewable energy, identifying which industries are most likely to benefit from digitalization and green energy investments. Finally, comparative studies between African regions or between Africa and other developing regions could offer a broader perspective on the factors driving or hindering green growth.

In conclusion, this study highlights the importance of carefully designed policies and investments in renewable energy, financial sector reforms, and ICT to foster green growth in Africa. By addressing region-specific challenges and leveraging unique opportunities, African countries can pave a sustainable path towards economic development, contributing to global environmental goals and advancing the knowledge-based economy.

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