International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2024, 14(5), 509-519.

Analyzing the Dynamics: Asymmetric Effects of Economic Growth, Technological Innovation, and Renewable Energy on Carbon Emissions in Africa

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Received: 04 April 2024 **Accepted:** 17 July 2024 **DOI:** https://doi.org/10.32479/ijeep.16488

ABSTRACT

This study examines the interactions among economic growth, technological innovation, renewable energy consumption, and carbon emissions in Africa using advanced econometric methods. Panel data analysis reveals both symmetric and asymmetric impacts on carbon emissions, showing how economic and technological variables contribute to environmental outcomes. The augmented mean group (AMG) and common correlated effects mean group (CCEMG) estimators address cross-sectional dependence and heterogeneity, ensuring robust results. Findings indicate that positive economic growth increases emissions, while economic downturns significantly reduce emissions. The study underscores the need for strategic policies that leverage technological innovations and renewable energy to promote sustainable development in African economies, balancing economic growth with environmental protection.

Keywords: Carbon Emissions, Renewable Energy, Panel Data Analysis, Asymmetric Effects, Cross-Section Dependence, Nonlinear Autoregressive Distributed Lag
JEL Classifications: Q53, Q54, Q56, C23, C32, C33

1. INTRODUCTION

In recent decades, the world has witnessed rapid industrialization, technological progress, and unprecedented economic growth. However, this progress has also coincided with increased environmental degradation and rising levels of carbon emissions. Since the mid-18th century, as noted by Liao et al. (2018), the global economy has seen significant growth but at the cost of considerable ecological damage, including pollution and climate change. This growth often entails heightened resource consumption, leading to adverse ecological impacts (Merko et al., 2019). Moreover, environmental degradation and climate change threaten the global economy's growth trajectory, underscoring the importance of sustainable development on the international stage (Wada et al., 2021).

Over the past three decades, numerous initiatives and programs aimed at fostering sustainable economic growth have been introduced. Yet, achieving sustainability remains elusive for many nations due to political reluctance, path dependencies, and a lack of international collaboration (Leal Filho et al., 2020). To address these challenges, the United Nations unveiled the 2030 Agenda for Sustainable Development in 2015, further complemented by the ratification of the Paris Agreement in 2025 by 196 nations, targeting net-zero emissions by 2050 and capping global temperature rises (UNFCCC, 2015).

However, progress towards the Sustainable Development Goals (SDGs) and the Paris Agreement remains inconsistent. Numerous countries continue to grapple with significant challenges, including poverty, inequality, and environmental degradation

(Alaganthiran and Anaba, 2022; Osadume and University, 2021). These global challenges highlight the need for "Green Growth" strategies, which seek a balance between economic growth and reduced environmental impacts by incorporating environmental considerations into economic strategies and endorsing sustainable practices across all sectors (Ferreira et al., 2023).

Africa, a continent rich in natural resources and undergoing robust economic transformations, is at a critical juncture. While many African nations strive to improve their economic stature and lift millions out of poverty, they also face mounting environmental challenges exacerbated by rapid urbanization, inefficient energy consumption, and limited adoption of renewable energy technologies. Despite the region's relatively low per capita carbon emissions, its contribution to global emissions is poised to grow significantly with the expansion of industrialization and population growth.

Research on the relationship between economic growth and environmental impact often highlights the Environmental Kuznets Curve (EKC) hypothesis, which suggests an inverted U-shaped relationship between per capita income and environmental degradation. According to this hypothesis, as economies grow, environmental degradation initially worsens but eventually improves once countries achieve higher levels of income and develop more robust environmental policies and cleaner technologies. Nevertheless, the applicability of the EKC hypothesis remains contentious, particularly in Africa, where economic structures, energy consumption patterns, and technological capacities vary greatly.

This study seeks to comprehensively investigate the symmetric and asymmetric effects of economic growth, technological advancement, and renewable energy consumption on carbon emissions in Africa. Our focus on Africa is driven by the region's distinctive socio-economic and environmental landscape, which necessitates tailored policy solutions to achieve sustainable growth. By employing advanced econometric modeling techniques such as the nonlinear autoregressive distributed lag (NARDL) model, we aim to uncover the nuanced relationships between these variables and their impact on carbon emissions.

Understanding these relationships is crucial in formulating effective strategies that balance economic progress with environmental stewardship. In particular, the adoption of renewable energy technologies, coupled with sound policy frameworks that incentivize green investments, can help Africa transition to a low-carbon economy. Furthermore, technological advancements must align with sustainable practices to ensure that the continent's growth trajectory is resilient and inclusive.

In this paper, we provide a detailed analysis of the factors influencing carbon emissions in Africa, with particular emphasis on economic growth, technological innovation, and energy consumption. We begin by reviewing the existing literature to highlight key insights and knowledge gaps. Subsequently, we discuss our methodology and data collection approach, offering a comprehensive view of the econometric models utilized. Finally, we present the results of our analysis, providing critical insights into the complex dynamics shaping carbon emissions in Africa, and conclude with policy recommendations that could guide the region toward a sustainable and prosperous future.

2. LITERATURE REVIEW

The existing literature provides a comprehensive understanding of the intricate relationships between economic growth, technological innovation, energy consumption, and carbon emissions. Researchers have employed various methodologies and frameworks to analyze these dynamics across diverse geographical regions and economic contexts. Studies investigating the Environmental Kuznets Curve (EKC) hypothesis, decoupling trends, and regional disparities highlight the challenges and opportunities in achieving sustainable development goals. Moreover, the literature emphasizes the multifaceted nature of technological innovation and its capacity to drive economic progress while simultaneously mitigating environmental degradation. These studies collectively offer critical insights into the pathways through which nations can effectively manage growth while addressing the pressing issue of carbon emissions.

2.1. The Relationship between Economic Growth and Carbon Emission

Narayan et al. (2016) investigated the relationship between economic growth and carbon dioxide emissions across 181 countries, using a cross-correlation approach. Their findings supported the Environmental Kuznets Curve (EKC) hypothesis in 21 countries, while 49 nations, particularly high-income ones, are poised to reduce emissions as future income growth progresses.

Yang et al. (2021) analyzed the decoupling of global economic growth from carbon emissions through data from 78 regions (2000-2017), identifying significant regional differences. Technological advancements in energy efficiency facilitated progress in Europe and North America, while rapid economic expansion in Asia limited global decoupling efforts.

Schröder and Storm (2020) explored the feasibility of decoupling economic growth from carbon emissions, employing the Kaya identity and Carbon-Kuznets-Curve framework. While high-income countries exhibited weak decoupling evidence, global emissions still rose with per capita GDP, underscoring the urgent need for deeper de-carbonization strategies to stabilize global warming.

In their analysis of China, Zhang and Cheng (2009) confirmed that GDP growth drives energy consumption, which in turn increases carbon emissions. However, they suggest that China could pursue energy conservation policies without compromising long-term economic growth.

Expanding on regional insights, Esso and Keho (2016) assessed 12 Sub-Saharan African nations and revealed varied causality patterns between energy consumption, economic growth, and carbon emissions. Their study highlighted the challenges of balancing economic expansion and environmental protection.

2.2. The Relationship between Technological Advancement and Carbon Emission

Technological innovation is seen as a key variable in reducing carbon emissions. However, the literature offers diverse perspectives on this relationship due to variations in technological trajectories and regional industrial activities.

Ali et al. (2016) emphasized the dual impact of technological innovation on CO_2 emissions in Malaysia, as it could either promote growth and enhance preservation or exacerbate emissions. The study called for investments in green technologies to align financial and technological growth with environmental benefits.

Zhang et al. (2016) demonstrated China's shift towards low-carbon technology after 2000, resulting in significant carbon efficiency improvements. However, such gains were not uniform across sectors, calling for nuanced approaches considering sector disparities.

In analyzing investments in China's energy sectors, Khan et al. (2020) reiterated that technological innovation in renewable energy significantly reduced emissions. However, the environmental benefits were counterbalanced by non-renewable investments, emphasizing strategic re-evaluation of investment portfolios.

Wang et al. (2020) examined the N-11 countries and confirmed that technological innovation, coupled with human capital and renewable energy consumption, can curtail emissions. Their research pointed to the necessity of tailored policies and innovation paths.

Focusing on BRICS nations, Erdogan (2021) noted technological advancements in sustainable construction technologies effectively reduced emissions in the building sector, indicating complex regional interactions.

Lastly, Niu (2021) explored technological innovation in China's provinces, reaffirming strategic investment in low-carbon technologies. Collaboration between academia and industry could significantly mitigate environmental challenges.

In summary, technological innovation's relationship with carbon emissions is multifaceted. Successful innovation relies on aligning policies with sustainable practices and collaborative efforts among government, academia, and industry.

2.3. The Relationship between Energy Consumption and Carbon Emission

The relationship between energy consumption and carbon emissions is influenced by factors like economic structures, urbanization, technological progression, and policy frameworks.

Acaravci and Ozturk (2010) examined the link between energy consumption, emissions, and economic growth in European countries, highlighting nuanced interactions. They challenged the universal applicability of the EKC hypothesis, noting that unique economic conditions influence energy-economic dynamics.

Al-Mulali et al. (2013) revealed urbanization's significant influence on energy consumption and carbon emissions in the MENA region. Rapid urbanization triggers heightened energy demand and emissions, suggesting sustainable urban practices could indirectly reduce emissions.

Ren et al. (2015) focused on Shandong Province, China, illustrating how urbanization drives energy consumption and emissions. Their study underscored the urgent need for transformative energy strategies in emerging economies.

Synthesizing diverse studies, Waheed et al. (2019) elaborated on the paradoxical relationship between economic growth, energy consumption, and emissions. Developed nations showed some decoupling, while developing ones struggled to do so. Their comprehensive review advocated renewable energy adoption.

Sharif et al. (2019) contrasted renewable and non-renewable energy sources, providing strong evidence that renewable energy can significantly mitigate emissions. Their research underscored the importance of transitioning to green energy.

Musah et al. (2021) reaffirmed the EKC hypothesis within North Africa, noting urbanization and foreign investments also play a role. Their study suggested economic growth could harmonize with sustainability through renewable energy and regulated urbanization.

In conclusion, the relationship between energy consumption and emissions is far from straightforward. Integrated strategies, including urbanization control, renewable energy adoption, and economic regulation, are needed to address carbon emissions. These must be context-specific and aligned with regional developmental goals to promote socio-economic sustainability.

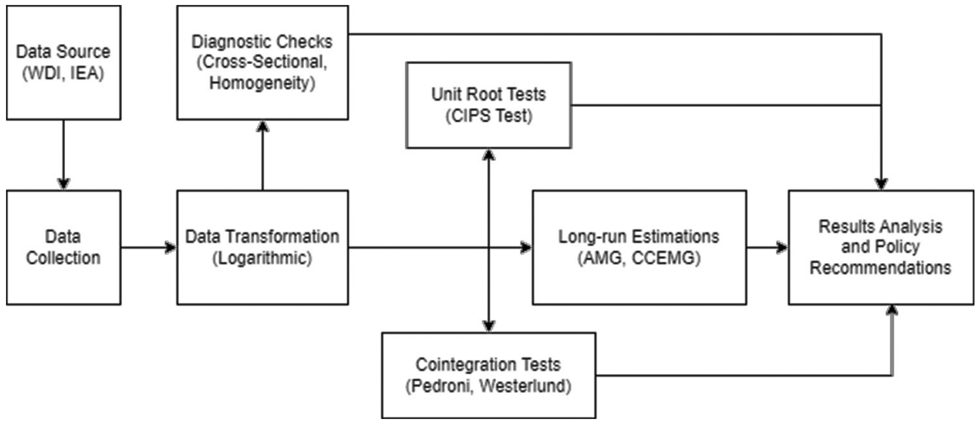
In summary, the literature review reveals a nuanced and complex picture of the global environmental landscape. The interplay between economic growth, technological advancement, energy consumption, and carbon emissions is influenced by regional, sectoral, and economic factors. While significant strides have been made toward understanding these relationships, the collective research underscores the necessity for targeted, context-specific policies that encourage sustainable practices, renewable energy adoption, and collaborative efforts between governments, industries, and academia. As the world continues to grapple with climate change, these insights are crucial in shaping strategies that balance economic development with environmental stewardship, ultimately fostering a more sustainable and resilient future.

3. MATERIALS AND METHODS

This section details the methodologies and data utilized to explore the symmetric and asymmetric influences of economic growth, technical advancement, and renewable energy sources on carbon emissions in Africa.

Figure 1 illustrates our research methodology. Starting from Data Sources (WDI, IEA), we proceed with Data Collection and

Figure 1: Methodological framework



Transformation (logarithmic adjustments). The transformed data undergoes Diagnostic Checks (cross-sectional, homogeneity) to ensure quality before Unit Root Tests (CIPS test) assess stationarity.

Cointegration Tests (Pedroni, Westerlund) follow, leading to Long-Run Estimations (AMG, CCEMG) that provide key relationships over time. After a thorough Results Analysis, we reach Conclusions that guide effective Policy Recommendations.

3.1. Data

The dataset for this study consists of annual environmental and economic variables collected from a variety of countries over a span of 16 years (2000-2016). Key variables include CO_2 emissions per capita (CO_2), Gross Domestic Product per capita (GDP), technological innovation (INV), renewable energy consumption (REE), population (POP), and natural resource rent (NRS). These variables are provided in their natural logarithmic forms to normalize the data distribution and to handle heteroscedasticity, enhancing the robustness of statistical estimates.

Data were meticulously compiled from various international databases, including the World Development Indicators (WDI) and the International Energy Agency (IEA), ensuring that each variable is accurately represented and reliable. The dataset encompasses a broad spectrum of economic, environmental, and demographic indicators, providing a comprehensive foundation for the subsequent econometric analysis. Table 1 provides a summary of the key variables used in the study, showcasing their descriptive statistics.

Table 1: Descriptive statistics of key variables

Variable	Mean	SD	Minimum	Maximum
lnCO_2 (CO_2 emissions)	8.054	2.264	−1.140	13.02
lnGDP (GDP per capita)	7.217	1.004	5.542	9.740
lnINV	3.461	0.486	1.609	4.357
lnREE	3.717	1.243	−2.813	4.588
lnPOP	2.142	1.595	−2.526	5.354
lnNRS	1.870	1.542	−6.749	4.484

INV: Technological innovation, REE: Renewable energy consumption, POP: Population, NRS: Natural resource rent, SD: Standard deviation, GDP: Gross domestic product

Table 1 serves as the empirical basis for investigating the relationships between economic growth, technological advancements, energy consumption, and carbon emissions. The study employs advanced econometric techniques to explore both the symmetric and asymmetric effects of these variables on carbon emissions, providing insights into the environmental impacts of economic and technological dynamics across different national contexts.

Another essential part of our study is the examination of the Gross Domestic Product (GDP) trends over the years across different countries included in our dataset. The GDP data provides insights into the economic growth patterns that are pivotal for understanding both regional and global economic dynamics.

Figure 2 illustrates the variation in GDP over the years. This visualization aids in identifying periods of significant growth or decline, which can be correlated with historical economic events, policy changes, or other external factors affecting the economies.

The graph displays a diverse range of economic trajectories. For instance, some countries show a consistent upward trend, indicative of steady economic growth, while others exhibit fluctuations that may correspond to economic crises or booms. Analyzing these trends helps us understand the broader economic impacts on environmental and technological variables discussed elsewhere in this study.

This longitudinal analysis forms the basis for deeper econometric investigation into the factors driving changes in GDP and their subsequent effects on carbon emissions and energy consumption patterns across the sampled countries.

To better understand the relationships between key economic and environmental indicators in our dataset, a correlation heatmap was plotted, as shown in Figure 3. The heatmap visually represents the correlation matrix, highlighting both the magnitude and direction of correlations between variables such as GDP Per Capita, CO_2 Emissions, Population, Annual GNI Growth, Trade Openness, and Institutional Quality. Positive correlations are indicated in shades of red, while negative correlations appear in shades of blue, with stronger correlations reflected by deeper hues. This visualization provides valuable insights into the interdependencies among these variables, revealing, for instance, a strong positive relationship

Figure 2: Annual GDP trends

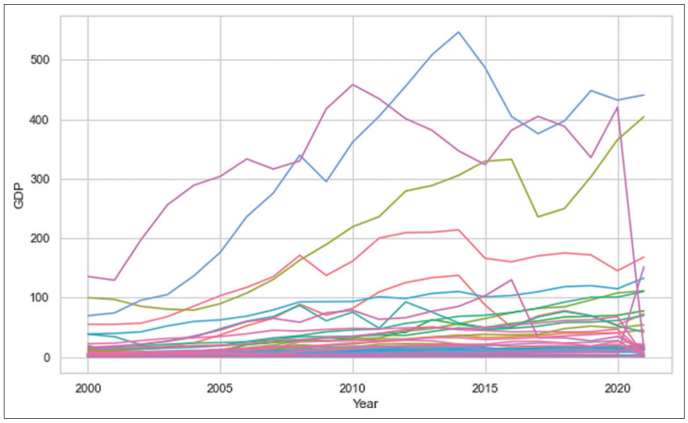
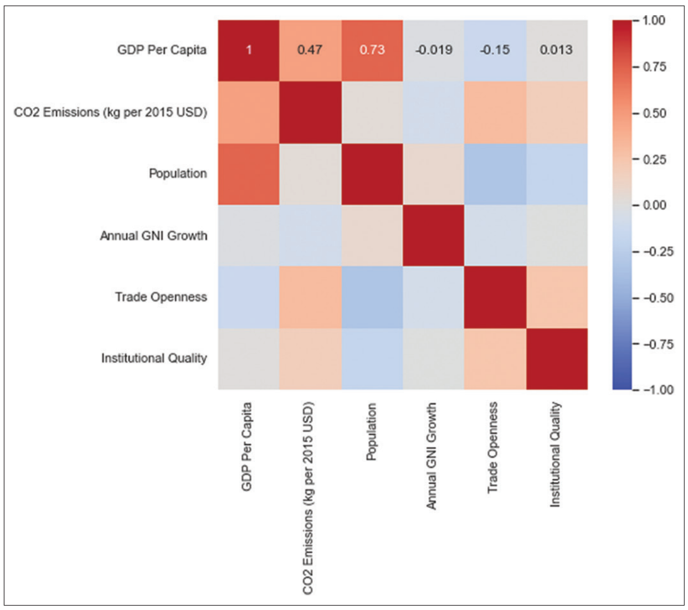


Figure 3: Correlation heatmaps



between GDP Per Capita and Trade Openness, while noting the inverse relationship between GDP Per Capita and Institutional Quality.

Scatter plots offer a visual examination of the relationship between GDP Per Capita and CO_2 Emissions, as shown in Figure 4. The plot reveals a positive correlation, where increases in GDP Per Capita generally coincide with higher CO_2 emissions. Notable outliers highlight variations among countries, possibly due to differences in industrialization, environmental policies, or energy consumption. Figure 5 further emphasizes this correlation by using a scatter plot with each point representing a country and showing the trend with a clear positive relationship.

3.2. Econometric Model

This research aims to examine both the symmetric and asymmetric influences of economic growth, technical advancement, and renewable energy sources on carbon emissions in Africa. The interrelationships between these variables can be mathematically expressed as follows:

$$CO_2 = f(GDP, INV, REE, POP, NRS) \quad (1)$$

In this equation:

CO_2: Carbon emissions per capita in metric tons

GDP: Real GDP per capita calculated using 2017 US$ prices

INV: Technological innovation

REE: Renewable energy consumption

POP: Population

NRS: Natural resource rent

To address heteroscedasticity, all relevant variables are transformed to their logarithmic forms. The following transformations are applied to Equations (1) and (2):

$$\ln CO_2 = \alpha + \beta 1 \ln GDP + \beta 2 \ln INV + \beta 3 \ln REE + \beta 4 \ln POP + \beta 5 \ln NRS + \varepsilon \quad (2)$$

where:

$\beta 1$ through $\beta 5$ represent the elasticities of CO_2 emissions concerning economic growth, technological innovation, renewable energy consumption, population, and natural resource depletion, respectively.

i and *t* represent individual cross-sections and time, respectively.

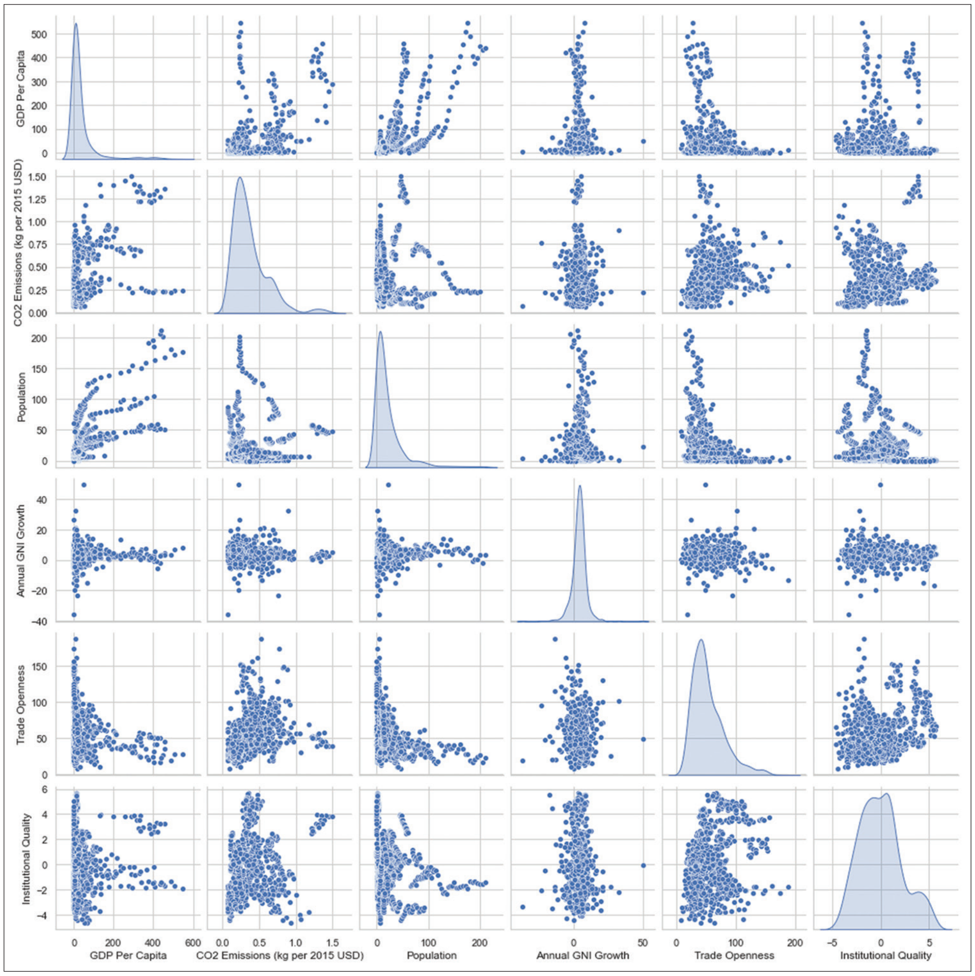
In the first stage of the econometric analysis, addressing cross-sectional dependence and heterogeneity is crucial to ensure consistent estimation outcomes. To achieve this, we conducted tests for cross-sectional dependence and heterogeneity using Pesaran's (2004) cross-sectional dependency and Pesaran's and Yamagata (2008) homogeneity tests. Acknowledging the potential presence of residual cross-sectional reliance and heterogeneity in panel data settings, the study proceeded to examine the integration properties in the second stage using the Cross-sectional Im, Pesaran, and Shin (CIPS) unit root test proposed by Pesaran (2007).

Next, the study employs panel cointegration tests, specifically the Pedroni (2004) and Westerlund (2007) tests, to confirm whether a long-term equilibrium relationship exists among the variables, despite potential short-term fluctuations. These tests are particularly valuable in panels where the assumption of individual unit roots might hold, but there still exists a possibility of a stable, long-term relationship across units.

Pedroni Test provides multiple test statistics, both within-dimension (based on residuals from individual panel regressions) and between-dimension (based on residuals averaged across the panel), allowing for comprehensive assessment of cointegration across diverse economic settings represented within the dataset.

On the other hand, Westerlund Test is designed to account for cross-sectional dependence, a likely feature in our data given the

Figure 4: Pair plots



economic interactions and environmental policies shared among African countries. It uses group statistics and panel statistics to provide a robust measure of the cointegration presence, even under the influence of common factors across units.

Upon establishing the presence of cointegration among the variables, the study advances to long-run estimation techniques that can adequately handle the identified cross-sectional dependencies and heterogeneities.

Augmented Mean Group (AMG) Estimator, developed by Bond and Eberhardt (2013), is used to estimate the long-run relationships while controlling for potential cross-sectional dependence and differential effects across countries. The AMG method incorporates a two-step procedure where the first step involves de-meaning the data with respect to time effects, and the second step averages the coefficients from country-specific regressions that include country-specific intercepts and slopes along with a common dynamic effect.

Introduced by Pesaran (2006), Common Correlated Effects Mean Group (CCEMG) Estimator addresses the issue of unobserved common factors that might influence the dependent variable across different countries. It involves the estimation of mean group coefficients with the inclusion of cross-section averages of all variables in the model, ensuring that the estimates are not biased by omitted common factors.

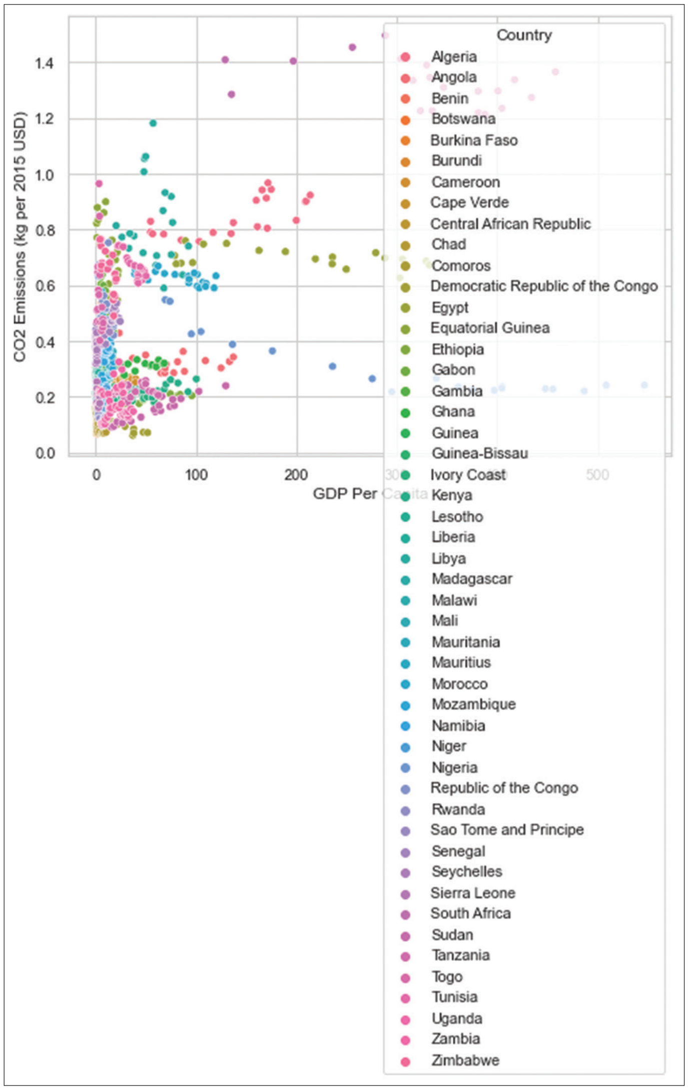
The application of these advanced econometric techniques provides robust insights into the long-term impacts of economic growth, technological innovation, and renewable energy consumption on carbon emissions. By accounting for the unique characteristics of each country within the dataset, as well as overarching common trends, the study ensures the reliability and relevance of its findings to policy formulation aimed at reducing carbon emissions in Africa.

The specified econometric model, as formulated in Equation (2), captures the logarithmic relationships among the variables, allowing for the interpretation of the estimated coefficients as elasticities. These elasticities represent the percentage change in CO_2 emissions for a one percent change in each of the independent variables, holding other factors constant. This model not only highlights the direct effects of these variables on emissions but also allows for the examination of potential nonlinearities and asymmetries through further extensions such as the Nonlinear Autoregressive Distributed Lag (NARDL) model.

Equation (2) is estimated using T^{-1} dummies in a first-difference form through the following panel regression model:

$$\Delta Y_{it} = \alpha_i + \sum_{j=1}^{p} \delta_{ij} D_t + \sum_{k=1}^{q} \beta_{ik} \Delta X_{ikt} + \varepsilon_{it} \tag{3}$$

Figure 5: GDP versus CO_2 Emissions



Here, Δ denotes the first difference operator with T^{-1} time dummies, where δ_{ij} represents the coefficients of D_t, α_i is the constant term, and β_{ik} through β_{iq} capture the parameter estimates of the differenced study variables.

In the second stage of the AMG estimation procedure, the parameter δ_{ij} from the first stage is transformed into λ_t which represents a common dynamic process. This transformation facilitates the modeling of a dynamic relationship among the variables. The transformation can be expressed as follows:

$$\lambda_t = \sum_{j=1}^{p} \delta_{ij} D_t \tag{4}$$

Where λ_t captures the common dynamic process among the variables, and δ_{ij} represents the standard dynamic process and estimated coefficients of each dummy.

Based on the provided information, we can infer that the cross-section panel model with T^{-1} as specified in Eq. (4) is adjusted before estimating the average parameter estimates in terms of country specifics. Therefore, for each explanatory variable specified in the study's model, the parameters to estimate can be computed using the following relation:

$$\hat{\beta}_{AMG} = \frac{1}{N} \sum_{i=1}^{N} \hat{\beta}_i \tag{5}$$

where $\hat{\beta}_{AMG}$ represents the AMG estimator.

To account for potential asymmetric relationships between variables, this study employs the nonlinear autoregressive distributed lag (NARDL) model developed by Shin et al. (2014) as follows:

$$Y_t = \beta_0 + \sum_{j=1}^{p} \beta_j^{+} \Delta GDP_{t-j}^{+} + \sum_{j=1}^{p} \beta_j^{-} \Delta GDP_{t-j}^{-} + \ldots + \varepsilon_t \tag{6}$$

In this context, ΔGDP_{t-j}^{+} and ΔGDP_{t-j}^{-} indicate the positive and negative partial sum process fluctuations within GDP. Similarly, ΔINV_{t-j}^{+} and ΔINV_{t-j}^{-} represent the positive and negative partial sum process fluctuations within *INV*. ΔREE_{t-j}^{+} and ΔREE_{t-j}^{-} denote the positive and negative partial sum process fluctuations within *REE*.

4. RESULTS AND DISCUSSION

4.1. Correlation Analysis

Table 1 presents a correlation analysis that sheds light on the relationships between the examined variables. The findings indicate that $LNCO_2$ positively correlates with LNGDP and LNPOP, meaning that as GDP and population densities increase, so do carbon emissions. Conversely, $LNCO_2$ exhibits a negative correlation with LNREE, suggesting that more significant investments in renewable energy are associated with lower carbon emissions. It is worth noting that the explanatory variables have low correlations, eliminating the possibility of multicollinearity with the selected explanatory factors.

4.2. Slope-Heterogeneity and Cross-Section Dependence

The CD tests in Table 2 strongly reject the null hypothesis of cross-sectional independence in all cases. This implies that there is residual cross-sectional connectedness within the panel data used. From an economic standpoint, shocks in one African country can spread to other member states due to their close economic interconnections. Additionally, the heterogeneity test results in Table 3 indicate that the null hypothesis of homogeneous slope coefficients for the study variables is once again rejected, pointing to heterogeneity issues across all models. Therefore, it is advisable to utilize a second-generation unit root test to evaluate the stationarity properties of the variables within the panel data.

The results presented in Table 3 showcase the outcomes of the CIPS and CADF unit root tests for both level I(0) and first difference I(1). The findings from these tests indicate that certain variables are non-stationary at their levels but become stationary when differenced using first-order differencing. This suggests that all observed variables are integrated at either I(0) or I(1).

Table 2: Correlation results

Variables	$lnCO_2$	lnGDP	lnINV	lnREE	lnPOP	lnNRS
$lnCO_2$	1.000					
lnGDP	0.262***	1.000				
lnINV	−0.016	0.207***	1.000			
lnREE	−0.156***	−0.699***	−0.120***	1.000		
lnPOP	0.722***	−0.298***	−0.090***	0.188***	1.000	
lnNRS	0.226***	−0.305***	−0.460***	0.225***	0.302***	1.000

***Indicates P<0.01,**Indicates P<0.05, *Indicates P<0.1. INV: Technological innovation, REE: Renewable energy consumption, POP: Population, NRS: Natural resource rent, GDP: Gross domestic product

Table 3: Slope-heterogeneity and cross-section dependence results

Test	Statistics	P
Slope-heterogeneity/homogeneity		
Delta	4.350***	0.000
Adjusted delta	5.615***	0.000
CSD test		
$lnCO_2$	0.73***	0.000
lnGDP	7.314***	0.000
lnINV	39.50***	0.000
lnREE	6.58***	0.000
lnPOP	30.03***	0.000
lnNRS	33.05***	0.000

***Indicates P<0.01,** indicates P<0.05, *Indicates P<0.1. CSD test: Cross-section dependence test, INV: Technological innovation, REE: Renewable energy consumption, POP: Population, NRS: Natural resource rent, GDP: Gross domestic product

Table 4: Panel unit-root test

Variables	CI	CI+T	CIPS I	CIPS I+T
$lnCO_2$	−1.334*	−3.205***	1.5245	−1.4779
lnGDP	0.092	−2.450**	1.6492	1.1504
lnINV	0.496	−7.859***	−0.1837	3.4498
lnREE	−1.669**	−3.378***	−1.4584*	0.7461
lnPOP	−0.958	1.190	3.4010	−0.9318
lnNRS	−4.701***	−8.194***	−1.5637*	−2.552
$D.lnCO_2$	1.504	−1.339*	−8.0402***	−4.6277***
D.lnGDP	1.240	0.884	−6.2764***	−6.5905***
D.lnINV	−0.177	−3.279***	−8.1328***	−7.0557***
D.lnREE	0.610	−1.026	−7.8164***	−8.4728***
D.lnPOP	4.453	4.156	−2.8598***	−1.1855
D.lnNRS	−1.688***	−5.054***	−11.5485***	−9.1373***

*** Indicates P<0.01,** indicates P<0.05, * indicates P<0.1. CI stands for CADF intercept, CI+T indicates CADF Intercept+Trend, CIPS I denotes CIPS Intercept, and CIPS I+T represents CIPS Intercept+Trend. CI: Confidence interval, INV: Technological innovation, REE: Renewable energy consumption, POP: Population, NRS: Natural resource rent, GDP: Gross domestic product

This information is crucial for determining the appropriate order of integration for each variable, which is essential for conducting further time-series analysis and modeling.

4.3. Cointegrating Test Result

Based on the results presented in Tables 4 and 5, it is evident that the Kao, Pedroni, and Westerlund cointegration approaches are used to investigate cointegration among the variables. The findings indicate that for the variables G_t, G_α and P_t the null hypothesis of no cointegration is rejected, suggesting a long-run association among them. However, for the variable P_α the null hypothesis is accepted, indicating no cointegration. Furthermore, when considering all estimated models, the Pedroni cointegration test consistently rejects the null hypothesis of no cointegration at the 1% level of statistical significance, indicating strong evidence in support of long-run cointegration relationships between the variables of interest. It's worth noting that the results from the Kao test also support the existence of cointegration, adding further validity to the findings. These results suggest that there are long-term relationships among the variables under consideration, which is crucial for understanding their interdependencies and dynamics over time.

4.4. Symmetric Long Run Results

The study concludes by examining the long-run elasticities of the explanatory variables—economic growth, technological innovation, renewable energy consumption, population, and natural resource depletion—with respect to CO_2 emissions using both the AMG and CCEMG estimation approaches. This analysis provides insights into the relationships between these factors and CO_2 emissions over the long term, contributing to a comprehensive understanding of the drivers of environmental impact within the studied context.

The result from table 6 reveals that there is a strong and positive relation between economic growth and CO_2 emissions in African countries. A 5% increase in economic growth (measured by AMG) leads to a 0.323% rise in CO2 emissions, while a 1% increase in economic growth (measured by CCEMG) results in a 0.392% increase in CO_2 emissions. This finding aligns with many African nations' rapid economic development and industrial activity. Industries heavily reliant on fossil fuels, such as manufacturing and transportation, significantly contribute to this environmental degradation.

4.5. Asymmetric Long Run Results

The results in Table 7 reveal several key insights into the asymmetric long-run impacts of economic growth, technological innovation, renewable energy consumption, population, and natural resource rent on carbon emissions. Both positive (LnGDP+) and negative (LnGDP-) fluctuations in GDP significantly affect carbon emissions, but with different magnitudes and directions. Positive changes in GDP result in a notable increase in emissions, while negative changes have a stronger decreasing effect, particularly in the CCE estimation. Technological innovation (LNINV+) exerts a significant negative impact on emissions, indicating that advancements are effective in reducing environmental impacts. Increased use of renewable energy (LNREE+) substantially reduces carbon emissions, while decreases in renewable consumption (LNREE-) exacerbate emissions, underscoring the importance of renewables. Population growth (LNPOP) shows mixed results, with a significant positive impact only in the AUG model.

Table 5: Kao and Pedroni cointegration tests

Test	Statistics 1	Statistics 2	Statistics 3
Kao	ADF 0.1841**(0.0270)	MDF 0.9663 (0.1670)	UDF 0.4131**(0.0398)
Pedroni	Panel-ADF -6.6326***(0.0000)	Panel-PP -7.7151***(0.0000)	Group-PP 4.4558***(0.0000)
	Westerlund cointegration tests		
Test	Statistics 1		Statistics 2
Westerlund	P_t 1.3071* (0.0956)		P_α −1.0748 (0.1412)
	G_t 0.7818*** (0.000)		G_α −1.7194** (0.0428)

*** indicates P<0.01,** indicates P<0.05, * indicates P<0.1

4.6. Comparative Analysis of the Results

Our study aligns with previous research, such as Narayan et al. (2016) and Yang et al. (2021), confirming a positive correlation between economic growth and carbon emissions in support of the Environmental Kuznets Curve (EKC) hypothesis. This trend is especially prevalent in the early stages of development, where rising GDP often leads to increased emissions. Additionally, our work parallels Ali et al. (2016) and Zhang et al. (2016) by highlighting the dual role of technological innovation in stimulating economic growth while reducing environmental impacts. Technological advancements typically correlate with reduced emissions, underscoring the importance of investing in green technologies. Similarly, our research shows that renewable energy consumption correlates with lower emissions, echoing Sharif et al. (2019) and supporting a transition to renewable energy for sustainability.

While studies like Yang et al. (2021) and Esso and Keho (2016) emphasize regional disparities in decoupling economic growth from emissions, our research provides insights specifically relevant to the African context, which are vital for regional policymaking. Our advanced econometric methods, such as AMG and CCEMG estimators, account for cross-sectional dependence and heterogeneity more effectively than previous studies. This methodological rigor bolsters the reliability of our findings across African countries. Additionally, our research provides tailored policy recommendations for African nations, emphasizing the long-term elasticities of factors influencing CO_2 emissions to guide economic and environmental strategies. By modeling asymmetric influences of economic shocks on environmental outcomes through the NARDL model, our study fills a gap in existing literature, revealing how positive and negative economic changes impact emissions differently. Including natural resource rent (NRS) in our model emphasizes the unique economic structures of resource-rich African nations, which is critical for assessing environmental impacts.

The Asymmetric Long Run Results in Table 7 reveal that both positive and negative GDP fluctuations impact carbon emissions significantly. Positive GDP changes lead to increased emissions, while negative changes have a more substantial effect in reducing emissions, highlighting the importance of nuanced economic policies that consider both economic growth and volatility.

Our study also emphasizes the positive impact of technological innovations (LNINV+) on emissions reduction, where even small advancements yield significant environmental benefits. Decreases in innovation activities (LNINV-) have a less pronounced but still notable negative impact, suggesting a strong relationship between innovation intensity and emission levels.

Table 6: Augmented mean group and common correlated effect results

Variables	AMG (model 1)	CCEMG (model 2)
lnGDP	0.323*** (0.108)	0.392*** (0.127)
LNINV	−0.0774* (0.0446)	−0.0173 (0.0650)
LNREE	−3.001*** (0.541)	−3.292*** (0.592)
LNPOP	0.738*** (0.278)	0.629* (0.374)
LNNRS	0.0173 (0.0184)	0.0298 (0.0207)
c_d_p	0.729** (0.295)	N/A
Constant	17.25*** (2.378)	17.81*** (3.764)
Walda Test	31.87	29.16
Sigma	0.075	0.044
Observations	1077	1077
Number of ID	49	49

*** indicates P<0.01,** indicates P<0.05, * indicates P<0.1. NA: Not available, CCEMG: Common correlated effects mean group, AMG: Augmented mean group

Table 7: Asymmetric long run results

Varıables	AUG	CCE
LnGDP+	0.293*** (0.179)	0.862*** (0.296)
LnGDP-	−0.780*** (0.995)	−1.953*** (2.149)
LNINV+	−0.181*** (0.160)	−0.220*** (0.279)
LNINV-	−0.0128*** (0.108)	−0.0511*** (0.154)
LNREE+	−3.616*** (0.670)	−4.251*** (0.936)
LNREE-	−3.086*** (0.627)	−2.864*** (0.655)
LNPOP	0.610** (0.310)	0.843 (2.079)
LNNRS	0.00650 (0.0158)	0.0125 (0.0345)
c_d_p	0.694** (0.213)	N/A
Constant	6.276*** (0.810)	3.194 (3.547)
Walda test	47.08	45.95
Sigma	0.0381	0.0197
Observations	1,078	1,078
Number of ID	49	49

*** indicates P<0.01,** indicates P<0.05, *indicates P<0.1. CCE: Common correlated effects

Regarding renewable energy (LNREE+ and LNREE-), our results reinforce the global call for increased renewable energy use. Reductions in renewable energy consumption are directly linked to higher emissions, emphasizing the importance of continuous investment in this sector.

Overall, our comparative analysis underscores that while global trends exist, the unique dynamics of Africa require tailored strategies to manage growth and sustainability. This approach should integrate symmetric and asymmetric economic impacts to guide effective policies balancing economic activity with environmental outcomes.

5. POLICY RECOMMENDATIONS

Based on the econometric analysis, which demonstrated significant relationships among GDP, renewable energy consumption, and carbon emissions, as well as the asymmetric impacts of economic fluctuations, we recommend the following targeted policy measures for sustainable development in Africa:

1. Sustainable Energy Transition: Given the significant negative correlation between renewable energy consumption and carbon emissions, African nations should accelerate investments in renewable resources such as solar, wind, and hydropower. Policies should include providing subsidies and incentives for renewable energy production, which will not only help reduce carbon emissions but also improve energy security, as indicated by the positive effect of GDP on CO_2 emissions (β1 in Equation (2)).
2. Carbon Pricing and Taxes: To further reduce carbon emissions, implementing carbon pricing mechanisms such as taxes or cap-and-trade systems could be effective. This will incentivize businesses to adopt cleaner technologies, supported by the findings where GDP growth was positively linked to emissions, suggesting that economic activities currently contribute significantly to carbon emissions (β2 in Equation (2)).
3. Technological Innovation Support: The study found a strong linkage between technological innovation and reduced emissions (β3 in Equation (2)). As such, governments should enhance support for R&D in clean technologies through grants or tax credits, fostering an environment where technological innovations can thrive.
4. Addressing Asymmetry in Economic Shocks: Policies should account for the asymmetrical effects of economic changes observed in our study. During periods of economic downturn, proactive measures should be taken to sustain investments in green technologies and renewable energies to avoid an increase in emissions due to reduced economic activity.
5. Regional Cooperation: Given the cross-sectional dependence detected in our analysis, regional cooperation is essential. Shared initiatives and best practices can lead to better outcomes in managing environmental impacts and implementing sustainable policies.
6. Inclusive Economic Growth: Policies that ensure economic growth also includes improvements in social equity and access to opportunities will help manage the environmental impact as economies grow. Special attention should be given to empowering marginalized communities, ensuring their inclusion in the transition to a green economy.
7. Integrated Urban Planning: Urban planning that integrates green spaces, efficient public transport, and sustainable building practices will help mitigate the negative effects of urban population densities on carbon emissions, as reflected by the population coefficient (β4 in Equation (2)).
8. Strengthening Environmental Governance: To enforce the above policies effectively, strengthening institutional capacities to monitor, enforce, and adapt environmental regulations is crucial. This includes developing robust mechanisms for transparency and accountability in environmental governance.
9. International Collaboration: Collaboration with international bodies and developed nations can provide the necessary financial and technical support to implement these policies effectively. Such partnerships are crucial for transferring the necessary technologies and funding required for substantial investments in green technologies.

By implementing these recommendations, African nations can address the pressing challenge of balancing economic growth with environmental sustainability. The econometric evidence provided by this study highlights specific areas where policy effectiveness can be maximized, leading to long-term benefits for the continent's economy and its people.

6. CONCLUSION

This research emphasizes the critical need for sustainable economic development strategies in Africa. Our study delved into the intricate relationships between economic growth, technological advancement, and renewable energy consumption, highlighting their asymmetric and nuanced effects on carbon emissions.

Our findings suggest that while economic growth and population density are positively correlated with carbon emissions, renewable energy consumption can significantly mitigate environmental impact. Moreover, the asymmetric long-run results emphasize that positive economic growth leads to increased emissions, whereas negative economic shifts tend to reduce emissions more significantly. This underscores the importance of policies that are prepared to address these asymmetries and ensure a balanced response during economic downturns.

The cross-sectional dependency and heterogeneity in the data illustrate the interconnectedness of African economies and the diverse economic structures across the continent. Despite the varied economic landscapes, the results reveal common patterns: a greater reliance on renewable energy and investment in technological innovation is essential for reducing emissions while maintaining economic growth.

The adoption of advanced econometric techniques, such as the NARDL model, has allowed us to uncover the complex interplay between these variables. Policymakers must consider the region's socio-economic and environmental dynamics when designing policies aimed at achieving sustainable growth. Specifically, they should focus on incentivizing the adoption of renewable energy technologies, improving access to green financing, and developing comprehensive policy frameworks that integrate environmental objectives into broader economic goals. Additionally, proactive measures should be taken to sustain investments in green technologies and renewable energies even during economic downturns to prevent a significant rise in emissions.

In conclusion, the path to sustainable development in Africa hinges on a balanced approach that promotes economic progress while ensuring environmental stewardship. This requires coordinated regional and international efforts, coupled with a clear commitment to implementing sound policies that foster technological innovation and reduce reliance on carbon-intensive energy sources. Ultimately, such an approach can help African nations achieve a prosperous and sustainable future.

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