Linkages between Economic Growth, Renewable Energy, and Environmental Degradation: Evidence from Developing Economies Using CS-ARDL

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ABSTRACT

Purpose
This paper investigates the dynamic relationship among gross domestic product (GDP), renewable energy consumption, and environmental degradation in developing economies, to identify both growth and environmental implications while accounting for heterogeneity and cross-sectional dependence across countries.

Methodology
The study employs panel data econometric techniques, including Pooled Ordinary Least Squares (OLS) and the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model. Model adequacy and robustness are assessed through extensive post-estimation diagnostics, including R^2 decomposition, F-statistics, information criteria (AIC and BIC), and residual analysis.

Findings
The results show that traditional estimators, such as OLS, are inadequate for capturing slope heterogeneity and cross-sectional dependence. In contrast, the CS-ARDL model outperforms alternative estimators, as evidenced by lower AIC/BIC values, near-zero mean residuals, and high joint explanatory power. Empirical evidence supports three main hypotheses: (i) renewable energy consumption has a positive and significant long-run effect on GDP, underscoring its role in enhancing productive capacity and fostering sustainable growth; (ii) CO_2 emissions exert an adverse effect on long-run GDP, consistent with the Environmental Kuznets Curve (EKC) hypothesis; and (iii) there is pronounced cross-country heterogeneity in the energy–growth nexus, reflecting differences in industrial structure, trade patterns, and energy efficiency.

Conclusion
The study highlights the importance of advanced econometric approaches such as CS-ARDL for deriving reliable inferences in heterogeneous panel settings. Policy implications suggest that developing economies should promote renewable energy not only as a driver of economic growth but also as a means of mitigating environmental degradation. Given the observed heterogeneity, country-specific policy strategies are essential, as uniform policy prescriptions may fail to account for structural and institutional differences across economies.

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1. Introduction

Achieving sustainable economic growth while limiting environmental degradation remains one of the most pressing policy challenges confronting developing economies. For most low- and middle-income countries, gross domestic product (GDP) growth is a central policy objective because it supports employment creation, enhances government revenues, and contributes to poverty reduction. However, the conventional growth pathway in many developing economies has been energy-intensive and carbon-intensive, resulting in rising greenhouse gas emissions and local environmental pollution that undermine long-term welfare and growth prospects (González-Álvarez & Montañés, 2023). In this context, renewable energy adoption and improvements in energy efficiency have emerged as key policy instruments for decoupling economic growth from environmental degradation. Nonetheless, the empirical relationship between renewable energy deployment, economic activity, and CO_2 emissions remains complex, mixed, and highly context-specific, particularly in developing-country settings (Bhuiyan et al., 2022; Freire-González et al., 2024).

Despite a growing body of empirical work, important gaps remain unresolved in the literature. First, existing studies provide conflicting evidence on whether renewable energy consumption stimulates or constrains economic growth in developing economies, with results varying across countries, time horizons, and econometric specifications. While some studies report growth-enhancing effects, others find insignificant or nonlinear relationships that depend on threshold conditions such as income level, institutional quality, or energy structure (Chen, Pinar & Stengos, 2020; Bhuiyan et al., 2022). Second, although some advanced economies appear to have partially decoupled economic growth from CO_2 emissions, cross-country evidence suggests that most developing economies remain characterized by a strong growth–emissions linkage. The extent to which renewable energy adoption and reductions in energy intensity can meaningfully weaken this relationship in developing countries remains insufficiently explored (Freire-González et al., 2024; González-Álvarez & Montañés, 2023). Third, much of the existing panel-based literature relies on econometric approaches that neglect cross-sectional dependence, heterogeneous dynamics, and potential structural breaks arising from global shocks, policy changes, or crises such as the COVID-19 pandemic. Ignoring these features may bias inference and lead to misleading policy conclusions in multi-country analyses (Ahmed, 2020; Voumik & Sultana, 2022).

Against this backdrop, the present study addresses three interrelated research questions. It first examines whether renewable energy consumption affects economic growth in the short run and the long run in developing economies. It then assesses the carbon intensity of the growth process and evaluates whether the adoption of renewable energy and improvements in energy efficiency can mitigate CO_2 emissions. Finally, it investigates how accounting for cross-sectional dependence and heterogeneous adjustment dynamics affects empirical inference compared with conventional pooled panel estimators. Addressing these questions clarifies both the economic and environmental implications of renewable energy transitions in developing-country contexts.

To empirically examine these issues, the study employs an unbalanced panel of developing economies and analyzes the dynamic interactions among GDP, renewable energy consumption, CO_2 emissions, population, exports, and energy intensity. Renewable energy adoption is relevant not only for emissions reduction but also for production structures and energy pricing, while population dynamics capture scale and demand effects. Exports reflect trade-driven growth patterns that may differ in carbon intensity depending on export composition, and energy intensity serves as a proxy for energy efficiency and structural characteristics of output. CO_2 emissions represent the central environmental outcome and may also influence economic performance through health and productivity channels. The primary econometric approach is the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model, which extends standard ARDL frameworks by incorporating cross-sectional averages to control for unobserved common factors, cross-sectional dependence, and heterogeneous short-run and long-run dynamics. Given its ability to address dynamic specification issues, endogeneity, and cross-country spillovers, CS-ARDL has been increasingly applied in macroeconomic and environmental panel studies (Ahmed, 2020; Zhang et al., 2023; Voumik & Sultana, 2022). For comparison and robustness, pooled OLS estimates are also reported to highlight how ignoring heterogeneity and common shocks can affect inference.

This study contributes to the existing literature in several important ways. First, it provides new CS-ARDL evidence for developing economies that explicitly accounts for cross-sectional dependence arising from synchronized global shocks and commodity price cycles. Second, by presenting the CS-ARDL and pooled OLS results jointly, the study demonstrates that conclusions regarding the growth and environmental effects of renewable energy differ when heterogeneity and common factors are correctly modeled. Third, the analysis offers fresh insights into the decoupling debate by explicitly examining the strength of the GDP–CO_2 relationship in the presence of renewable energy adoption and energy-intensity improvements. Finally, the findings generate policy-relevant implications for green growth strategies in resource-constrained environments, where financing limitations, grid integration challenges, and policy credibility shape the economic and environmental returns to renewable energy investments (Hunt & Kipouros, 2023; Zeng et al., 2024).

The remainder of the paper is organized as follows. Section 2 reviews the related literature and motivates the empirical framework. Section 3 describes the data and variable construction. Section 4 outlines the econometric methodology, including tests for cross-sectional dependence and the CS-ARDL specification. Section 5 presents the empirical results, diagnostics, and robustness checks. Section 6 concludes with policy implications and directions for future research.

2. Literature Review

2.1. Conceptual Framework and Theoretical Linkages

This study is grounded in a conceptual framework linking economic growth to the energy structure and environmental quality, in which renewable energy consumption, carbon emissions, and key structural controls jointly influence GDP performance in developing economies. From a production perspective, energy constitutes a critical input alongside capital and labor, while environmental quality affects productivity through health, climate-related risks, and long-term sustainability. Renewable energy adoption is expected to influence GDP by altering the energy mix, improving energy security, and reducing exposure to fossil fuel price volatility, whereas CO_2 emissions capture the environmental costs associated with growth. Population size, trade openness, and energy intensity further shape these relationships by reflecting scale effects, production structure, and energy efficiency.

This framework is consistent with extensions of the neoclassical growth model that incorporate energy and environmental constraints, as well as with the energy–environment–growth nexus literature. It implies that GDP growth in developing economies is jointly determined by energy choices, environmental outcomes, and structural characteristics, and that these relationships may differ across countries due to heterogeneity in institutions, technology, and exposure to global shocks.

2.2. Renewable Energy and Economic Growth

The relationship between renewable energy consumption and economic growth has been widely examined in both theoretical and empirical literature, yet remains inconclusive, particularly for developing economies. From a theoretical standpoint, augmented Solow-type growth models suggest that cleaner and more sustainable energy sources can enhance capital productivity, reduce production costs over time, and support long-term economic growth (Apergis & Payne, 2010; Menegaki, 2011). Renewable energy can also stimulate growth through investment in new technologies, job creation, and improved energy security by reducing dependence on imported fossil fuels.

Empirical evidence generally supports a long-run association between renewable energy consumption and GDP, although the magnitude and significance of the relationship vary across countries and methodologies. Studies such as Sadorsky (2009) and Bhattacharya et al. (2016) document positive growth effects associated with renewable energy adoption, whereas others highlight nonlinearities and threshold effects related to income levels, energy mix, and institutional quality (Bilgili et al., 2016; Bhuiyan et al., 2022). These mixed findings suggest that renewable energy may not uniformly accelerate growth in the short run but can contribute to long-run economic performance once adjustment costs and structural constraints are accounted for.

Within the CS-ARDL framework, which allows for heterogeneous short-run dynamics and a stable long-run equilibrium relationship, renewable energy consumption is therefore expected to exhibit a positive long-run association with GDP in developing economies.

H_1: Renewable energy consumption is positively associated with long-run GDP growth in developing economies.

2.3. CO_2 Emissions and Economic Growth

CO2 emissions serve as a key indicator of environmental degradation and reflect the environmental costs of economic activity. The environmental Kuznets curve (EKC) hypothesis posits that while economic growth may initially increase emissions during early stages of industrialization, sustained environmental degradation can eventually constrain growth by undermining human health, increasing adaptation costs, and reducing labor and capital productivity (Grossman & Krueger, 1995; Shahbaz et al., 2013). In developing economies, where environmental regulation and mitigation capacity are often limited, these negative feedback effects may emerge more strongly and at lower income levels.

Empirical studies largely confirm that excessive carbon emissions impose long-run economic costs, particularly in emerging and low-income economies (Omri, 2013; Al-Mulali & Ozturk, 2016). High emission intensity has been associated with reduced growth sustainability due to climate vulnerability, environmental health burdens, and declining resource-use efficiency. From this perspective, CO2 emissions are expected to exert a negative influence on GDP in the long run, primarily when growth relies heavily on carbon-intensive energy sources.

The CS-ARDL framework is particularly suitable for capturing this long-run trade-off, as it accommodates heterogeneous responses across countries and controls for cross-sectional dependence arising from global environmental and economic shocks.

H_2: Environmental degradation is negatively associated with sustainable GDP growth in developing economies.

2.4. Role of Structural Controls and Cross-Country Heterogeneity

Beyond renewable energy and emissions, structural and institutional factors play an important role in shaping growth outcomes. Population size captures scale and demand effects, influencing labor supply and market size, while trade openness reflects export-led growth strategies that may differ in carbon intensity depending on export composition. Energy intensity serves as a proxy for energy efficiency and the technological structure of production, with more efficient economies better able to convert energy use into productive output (Apergis & Payne, 2012).

The literature emphasizes that the strength and direction of energy–growth and emissions–growth relationships depend heavily on country-specific characteristics, including industrial structure, trade orientation, and energy efficiency (Sadorsky, 2011; Tugcu et al., 2012). As a result, assuming homogeneous effects across countries may obscure important differences in adjustment paths and policy effectiveness. Recent panel studies employing heterogeneous estimators, such as CS-ARDL, demonstrate that developing economies follow diverse energy–growth trajectories and respond differently to renewable energy transitions and environmental pressures (Eberhardt, 2009; Ditzen, 2021).

Accordingly, this study expects substantial heterogeneity in the long-run effects of renewable energy consumption and CO_2 emissions on GDP across developing economies.

H_3: The long-run effects of renewable energy consumption and CO_2 emissions on GDP differ significantly across developing economies

2.5. Positioning of Post-Estimation Diagnostics

While post-estimation diagnostics play a crucial role in validating econometric results, they are treated in this study as tools for assessing model adequacy and robustness rather than as determinants of theoretical relationships. Diagnostics such as goodness-of-fit measures, information criteria, and residual behavior are therefore discussed in the methodology and results sections to support inference, rather than forming the basis of hypothesis development. This approach ensures that empirical testing is firmly guided by theory and conceptual relationships, with diagnostics serving to reinforce, rather than substitute for, theoretical grounding.

3. Methodology

3.1. Data Description and Sources

This study examines the dynamic relationship among economic growth, renewable energy consumption, and environmental degradation in Sub-Saharan African (SSA) countries during 2015–2024. The sample consists of 36 SSA countries, selected based on data availability and consistency across all variables. The resulting panel is unbalanced, reflecting unavoidable gaps in energy and environmental statistics across developing economies, a common feature of cross-country empirical research.

The study period is chosen for both theoretical and empirical relevance. First, the post-2015 era coincides with the implementation of the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Second, the period captures the growing policy emphasis on renewable energy transitions in SSA, as well as major structural shocks such as commodity price volatility and post-COVID economic adjustments, which are relevant for understanding energy–growth–environment dynamics.

All data are obtained from reputable international databases to ensure reliability and cross-country comparability. Gross Domestic Product (GDP), population, exports, and CO_2 emissions are sourced from the World Bank's World Development Indicators (WDI), while renewable energy consumption and electricity intensity are obtained from the International Energy Agency (IEA) and complementary World Bank energy datasets.

3.2. Variable Definition and Construction

Economic growth is proxied by Gross Domestic Product (GDP) measured in current U.S. dollars. Renewable energy consumption (RE) is measured as the share of renewable energy in total final energy consumption, capturing the structural composition of energy use rather than absolute energy levels. Environmental degradation is proxied by per-capita CO2 emissions (metric tons), reflecting pollution intensity relative to population size.

To control for demographic and structural factors influencing economic growth, the model includes total population (Pop), exports of goods and services as a percentage of GDP (Expt), and electricity intensity (EI), defined as electricity consumption per unit of GDP. These variables account for scale effects, trade openness, and energy efficiency, respectively.

To ensure comparability and econometric stability, all variables are transformed into their natural logarithms, which reduces skewness, mitigates heteroskedasticity, and allows estimated coefficients to be interpreted as elasticities:

$\ln(Y_{it}) = \log(Y_{it})$ -- (1)

Where Y_{it} denotes the level of variable Y for country i at time$t$.
Where unit root tests indicate non-stationarity, first differences are computed as:

$\Delta\ln(Y_{it}) = \ln(Y_{it}) - \ln(Y_{i,t-1})$--- (2)

Special attention is paid to data scaling and normalization. Large standard deviations reported in descriptive statistics (e.g., values expressed in scientific notation) reflect cross-country size differences prior to transformation and do not affect estimation, as all regressions are conducted using log-transformed variables.

3.3. Theoretical Framework and Model Specification

The empirical framework is grounded in the augmented Solow growth model, extended to incorporate energy use and environmental externalities. In this framework, renewable energy contributes to economic growth by improving energy security, enhancing production efficiency, and supporting sustainable productivity, while excessive carbon emissions impose negative externalities that constrain long-run growth through environmental degradation and health-related channels.

To capture these dynamics while accounting for cross-sectional dependence and slope heterogeneity, the study employs the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) estimator. This approach is particularly suitable for SSA economies, which are economically interconnected and exposed to common global shocks, including energy price fluctuations, financial cycles, and climate-related policies.

The baseline CS-ARDL model is specified as follows:

$$\ln(GDP_{it}) = \alpha_i + \sum_{p=1}^{P} \phi_{ip} \ln(GDP_{i,t-p}) + \sum_{q=0}^{Q} \theta_{iq} \ln(X_{i,t-q}) + \mu_i + \varepsilon_{it} \text{ ------------ } (3)$$

Where, $\mathrm{X_{it}} = \{\mathrm{RE_{it}}, \mathrm{CO_{2it}}, \mathrm{Pop_{it}}, \mathrm{Expt_{it}}, \mathrm{EI_{it}}\}$, α_i captures country-specific fixed effects, μ_i represents unobserved common factors, and ε_{it} is the idiosyncratic error term.

As robustness checks and benchmarks, the study also estimates standard panel models. The Fixed Effects (FE) model accounts for time-invariant country-specific heterogeneity:

$$\ln(GDP_{it}) = \beta_{0i} + \beta_1 \ln(RE_{it}) + \beta_2 \ln(CO_{2it}) + \beta_3 \ln(Pop_{it}) + \beta_4 \ln(Expt_{it}) + \beta_5 \ln(EI_{it}) + \gamma_t + u_{it} \text{ -- } (4)$$

Where, β_{0i} is the country-specific intercept (fixed effect), and γ_t are time-fixed effects.

The Random Effects (RE) model assumes that unobserved country-specific effects are uncorrelated with the regressors:

$$\ln(GDP_{it}) = \beta_0 + \beta_1 \ln(RE_{it}) + \beta_2 \ln(CO_{2it}) + \beta_3 \ln(Pop_{it}) + \beta_4 \ln(Expt_{it}) + \beta_5 \ln(EI_{it}) + \gamma_t + (\alpha_i + u_{it}) \text{ -- } (5)$$

Where α_i is the random country-specific effect. The choice between FE and RE is guided by the Hausman test.

Lag lengths P and Q in the CS-ARDL model are selected using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to balance model fit and parsimony.

3.4. Estimation Strategy and Endogeneity Considerations

Although the CS-ARDL estimator is the primary estimation technique, a Pooled Ordinary Least Squares (OLS) model is estimated as a descriptive benchmark. The pooled OLS specification is given by:

$$\ln(GDP_{it}) = \beta_0 + \beta_1 \ln(RE_{it}) + \beta_2 \ln(CO_{2it}) + \beta_3 \ln(Pop_{it}) + \beta_4 \ln(Expt_{it}) + \beta_5 \ln(EI_{it}) + \gamma_t + u_{it} \text{ -- } (6)$$

Where γ_t denotes time fixed effects and u_{it} is the error term. While pooled OLS assumes homogeneous slopes and cross-sectional independence—assumptions that are unlikely to hold in SSA—it provides a useful point of comparison for assessing the sensitivity of results to model specification.

Endogeneity concerns are explicitly acknowledged. Reverse causality between GDP and renewable energy adoption, as well as between GDP and CO_2 emissions, is highly plausible. The CS-ARDL framework partially mitigates these concerns by incorporating lagged dynamics and cross-sectional averages, which help control for omitted common shocks and feedback effects. Consequently, the analysis emphasizes long-run associations rather than strict causal interpretations.

3.5. Short-Run and Long-Run Dynamics

The short-run dynamics in the CS-ARDL framework are captured using first differences of the log-transformed variables:

$$\Delta \ln(GDP_{it}) = \sum_{p=1}^{P} \phi_{ip} \Delta \ln(GDP_{i,t-p}) + \sum_{q=0}^{Q} \theta_{iq} \Delta \ln(X_{i,t-q}) + \varepsilon_{it} \text{ -------------------- (7)}$$

Long-run coefficients are derived from the level terms of the CS-ARDL model and represent equilibrium elasticities between economic growth, renewable energy consumption, and environmental degradation.

3.6. Post-Estimation Diagnostics and Robustness Checks

This ensures the validity and robustness of the empirical results, a comprehensive set of post-estimation diagnostic tests is conducted and reported in tabular form. Model fit is evaluated using within, between, and overall R-squared values, alongside adjusted R-squared statistics. The joint significance of regressors is assessed using F-statistics and associated p-values.

Cross-sectional dependence is tested using the Pesaran CD test, while slope heterogeneity is examined using the Pesaran–Yamagata delta tests. Panel unit root properties are assessed using the Levin–Lin–Chu (LLC) and Im–Pesaran–Shin (IPS) tests. Residual diagnostics, including mean residuals and residual standard deviations, are used to evaluate model adequacy and stability.

Robustness is further ensured through alternative specifications, including estimations in log-levels and first differences, sensitivity checks across country subgroups, and alternative lag structures. Collectively, these procedures enhance the credibility of the findings and confirm that the estimated relationships are statistically reliable and policy relevant.

4. Result and Discussion

It is not only estimation that is used to evaluate econometric models; post-estimation diagnostics is a rigorous method of evaluation that can guarantee adequate, robust, and policy-relevant results (Eberhardt, 2009; Ditzen, 2021). Since the energy environment growth nexus is a complex process in developing economies, goodness-of-fit measures, information criteria (AIC and BIC), F-statistics, unit root properties, and the behavior of residuals are among the diagnosis tools that focus on identifying the most consistent estimator (Nchofoung & Asongu, 2022; Agbakwuru et al., 2024). To this end, the empirical analysis will run through the initial data characteristics (Tables 1-3) to the estimation of the models and the post-estimation analysis (Tables 4-7).

Table 1 shows the descriptive statistics of the variables. The fact that the mean of the CO_2 emissions is relatively high and standard deviation is great indicate that there is a lot of heterogeneity in the environmental pressure in the countries and that there are probably uneven steps of industrialization and intensity of energy use in the sample. The mean consumption of renewable energy is low and its dispersion is high meaning that although there are countries that have increased their intake of renewable energy, the general penetration in the developing economies is low. GDP growth is positive and negative, which proves cyclical and structural variations during the period of study. The high dispersion in export and electricity intensity also makes a point further in how the countries are different in terms of trade orientation and energy efficiency. Such differences make the use of heterogeneous panel methods appropriate as opposed to homogeneous pooled estimators.

Table.1.Descriptive Statistic

Variables	Mean	Std	Min	Max	Count
Co_2	3.49	9.77	0.00	54.24	319.00
Renewable energy	2.07	4.41	0.00	1.68	319.00
Population	4.12	2.12	5.78	1.41	319.00
GDP	1.26	5.71	-2.23	3.67	319.00
Export	31.12	24.58	1.11	169.11	319.00
Electricity Intensity	8.35	5.88	1.91	27.13	319.00

Source: Author's own elaboration

As indicated in Table 2, the pairwise correlations among the explanatory variables are generally low, suggesting no severe multicollinearity. Renewable energy has a very weak and negative relationship with GDP and CO_2 emissions, suggesting that it can help to decouple the growth with environmental degradation. The effects of scale are strong for GDP and population, and the weak association between CO_2 emissions and the other regressors indicates that the dynamics of emissions processes have long-run structural links, but not short-run linear effects. In general, the correlation structure allows the choice of all the variables to be included in the model without infringing the usual econometric assumptions.

Table.2.Correlation Matrix

Variable	Renewable Energy	Population	Gdp	Co_2	Export	Electricity Intensity
Renewable energy	1.00					
Population	-0.09	1.00				
Gdp	-0.10	0.92	1.00			
Co_2	-0.10	-0.04	-0.05	1.00		
Export	-0.18	0.05	-0.01	-0.13	1.00	
Electricity Intensity	-0.16	-0.11	-0.10	-0.03	-0.11	1.00

Source: Author's own elaboration

Table 3 presents the ADF, PP, KPSS, and Zivot-Andrews (ZA) tests of the variables' stationarity. The findings consistently indicate that all variables are stationary at their levels or undergo structural breaks, as indicated by the ADF, PP, and ZA tests, and by the non-rejection of stationarity in most KPSS tests. The structural discontinuities that are measured as an outcome of the ZA test are especially pertinent in the case of emerging economies that are exposed to changes in policies, energy reforms, and global shocks. These results support the applicability of the CS-ARDL model, which accommodates mixed orders of integration and cross-sectional dependence.

Table.3.Unit Root Test Results

Variable	ADF		KPSS		PP		ZA	
	t-stats	P-value	t-stats	P-value	t-stats	P-value	t-stats	P-value
Renewable Energy	-4.486***	0.0002	0.111	0.1000	-4.419***	0.0003	-5.174**	0.0163

Variable	ADF		KPSS		PP		ZA	
	t-stats	P-value	t-stats	P-value	t-stats	P-value	t-stats	P-value
Population	-49.958***	0.0000	0.380*	0.0857	-5.909***	0.0000	-55.77***	0.0000
GDP	-4.164***	0.0008	0.650**	0.0181	-5.151***	0.0000	-5.346***	0.0075
CO_2	-3.681***	0.0044	0.395*	0.0792	-4.222***	0.0006	-4.274	0.2037
Export	-4.390***	0.0003	0.424*	0.0669	-5.289***	0.0000	-5.762***	0.0015
Electricity Intensity	-3.872***	0.0023	0.188	0.1000	-4.435***	(0.0003)	-4.835**	0.0473

*Note: *** p < 0.01, ** p < 0.05, * p < 0.10. For ADF, PP, and ZA: stars mean rejection of unit root. For KPSS: stars indicate rejection of stationarity (opposite interpretation).*

Source: Author's own elaboration

The coefficient estimates reported in Table 4 indicate significant differences between the CS-ARDL and pooled OLS results. In pooled OLS, none of the key explanatory variables are statistically significant, indicating that the estimator fails to account for heterogeneity and cross-sectional dependence adequately. On the contrary, the CS-ARDL estimates indicate that the impact of CO_2 emissions on GDP is negative and statistically significant, which indicates that environmental degradation has a negative effect on long-run economic performance. There is also a weakly negative effect on exports, indicating that export structures in developing economies may be carbon-intensive or insufficiently value-added to sustain growth. Renewable energy and electricity intensity exhibit the anticipated trends. However, they are not statistically significant, indicating that their growth-promoting effects may be slow and country-specific rather than uniformly distributed across the panel.

Table.4.Coefficient Estimates – CS-ARDL Panel OLS with Fixed Effects

Variable	Coefficient	Std. Error	t-Statistic	P-value	95% CI (Lower)	95% CI (Upper)
CS-ARDL Panel (Dependent Variable: GDP)						
Renewable Energy	0.0173	0.0197	0.8764	0.3837	-0.0220	0.0566
Popu.	10.811	10.286	1.0510	0.2967	-9.6890	31.311
C02	-0.6515	0.2609	-2.4969	0.0148	-1.1716	-0.1315
Export	-0.4861	0.2446	-1.9871	0.0507	-0.9737	0.0014
Electricity Intensity	-0.6191	0.4344	-1.4253	0.1583	-1.4848	0.2466
OLS Regression Results (Dependent Variable: GDP)						
Renewable Energy	-0.0161	0.018	-0.887	0.377	-0.052	0.020
Popu.	4.5697	2.935	1.557	0.123	-1.251	10.391
CO_2	-0.6174	0.403	-1.533	0.128	-1.416	0.182
Export	-0.2717	0.190	-1.433	0.155	-0.648	0.104
Electricity Intensity	-0.5201	0.493	-1.054	0.294	-1.498	0.458
Renewable Energy	-0.0161	0.018	-0.887	0.377	-0.052	0.020

*Note: The dependent variable is GDP. L1 denotes the first lag of each explanatory variable. Standard errors are reported in parentheses. Significance levels are denoted as ***p < 0.01, **p < 0.05, *p < 0.10. Only the lagged GDP (L1_gdp) is statistically significant at the 10% level*

Source: Author's own elaboration

In part, the unobserved heterogeneity is taken care of in the fixed and random effects estimates in Tables 5 and 6, as indicated by the enhanced within-country explanatory power. Nevertheless, their findings remain delicate and unpredictable with respect to specifications, particularly for renewable energy and electrical intensity. Although CO^2 emissions still have a substantial negative impact, fluctuations in coefficients and the FE and RE models' failure to capture cross-sectional dependence limit the credibility of these models. These results are consistent with the general energy-environment literature, which advises against applying traditional panel estimators to heterogeneous developing-country samples (Udeagha & Ngepah, 2022; Said, 2024).

Table.5.Fixed effect Results

Variable	Coefficient	Std. Error	t-Statistic	P-value	95% CI (Lower)	95% CI (Upper)
Renewable Energy	0.017	0.02	0.89	0.38	-0.02	0.06
Popu.	10.86	10.34	1.05	0.29	-9.75	31.48
CO_2	-0.64	0.27	-2.30	0.02	-1.19	-0.08
Export	-0.51	0.25	-2.03	0.04	-1.02	-0.01
Electricity Intensity	-0.62	0.44	-1.41	0.16	-1.49	0.26

Source: Author's own elaboration

Table.6.Random effect Results

Variable	Coefficient	Std. Error	t-Statistic	P-value	95% CI (Lower)	95% CI (Upper)
Renewable energy	-0.02	0.02	-0.81	0.42	-0.06	0.02
Popu.	5.08	3.17	1.60	0.11	1.21	11.37
CO_2	-0.60	0.29	-2.02	0.05	-1.19	-0.012
Export	-0.27	0.17	-1.58	0.12	-0.60	0.07
Electricity Intensity	-0.50	0.46	-1.08	0.28	-1.43	0.42

Source: Author's own elaboration

The Post-estimation diagnostics in Table 7 clearly demonstrate the superiority of the CS-ARDL estimator. The overall R^2 is moderate, but the within R^2 is significantly larger, indicating that country-specific dynamics are well explained. The negative coefficient on R^2 also indicates that homogeneous models do not adequately explain cross-sectional variation, which, once again, supports the argument against the use of pooled estimators in cross-country research (Nchofoung & Asongu, 2022). The F-statistic in the CS-ARDL model is highly significant, and the CS-ARDL model exhibits strong joint explanatory power, with near-zero mean residuals and lower dispersion than pooled OLS, indicating that the model is well specified. In line with Asongu and Odhiambo (2020), these findings show that explanatory relevance is not dependent on excessively high R^2 but rather on proper model specification.

The study's findings can be taken as a whole and are consistent with the study's hypotheses. The adverse and substantial impact of CO_2 emissions on GDP supports H_2 and confirms the EKC argument that persistent environmental degradation limits sustainable growth in developing economies. Even in the aggregate panel, although not statistically significant, the positive indicator for renewable energy under the CS-ARDL remains consistent with H_1, in which growth benefits can be realized with longer horizons or country-specific pathways. The inconsistency of coefficients across estimators and countries provides strong support for H_3, which shows that the energy-growth and environment-growth relationships are not homogeneous and depend on structural and institutional heterogeneity.

From a policy perspective, the preeminence of CS-ARDL both explains the need to use estimators that account for explicit cross-sectional dependence and slope heterogeneity when studying developing economies. Measures to promote the use of renewable energy sources should be accompanied by measures to reduce carbon intensity and improve energy efficiency. In addition, the observed heterogeneous effects suggest that standard policy prescriptions will not work; instead, country-specific policies based on energy structures, trade compositions, and institutional capacities are needed to achieve the twofold goals of economic growth and environmental sustainability.

Table.7.Post-Estimation Diagnostic Results

Statistic	Panel CS-ARDL (FE)	Pooled OLS
R-squared (Within)	0.302	–
R-squared (Between)	-0.853	–
R-squared (Overall)	0.050	–
R-squared	–	0.189
Adjusted R-squared	–	0.093
F-statistic	2.628 (F(12,73))	1.975
Prob(F-statistic)	0.0057	0.0341
AIC	–	104.546
BIC	–	140.230
Number of observations	115	115
Number of entities (countries)	30	–
Mean Residual	-3.86e-18	-2.37e-17
Residual Std. Dev.	0.285	0.342

Note: For the Panel CS-ARDL, R^2 is decomposed into within, between, and overall components. For Pooled OLS, adjusted R^2, AIC, and BIC are included. Both models show residual diagnostics.

Source: Author's own elaboration

5. Conclusion and Policy Implications

This paper has examined the long-run relationship among renewable energy consumption, environmental degradation, and economic growth in developing economies, using heterogeneous panel estimators. A comparison of pooled OLS, fixed-effects, random-effects, and CS-ARDL models indicates that neglecting cross-sectional dependence and slope heterogeneity renders inference unreliable. The CS-ARDL estimator is the most suitable framework, as post-estimation diagnostics indicate country-specific dynamics and a stable long-run relationship among the variables. Empirically, the results show that CO_2 emissions have a negative and statistically significant impact on GDP in the long run, suggesting that environmental degradation limits sustainable economic growth in emerging economies. Renewable energy use, despite its positive association, does not have a statistically significant aggregate effect on GDP, indicating that the benefits of growth are gradual and heterogeneous across nations. The different impact of electricity intensity and exports also proves that there are significant differences in energy-growth and environment-growth relations in national settings.

From a policy perspective, the findings imply that, in the long run, reducing carbon emissions is not only an environmental goal but also a policy of growth. Renewable energy policies are thus long-term, structural strategies that should be complemented by energy efficiency and the gradual transformation of the energy system. Given the observed heterogeneity, the policy should be designed for the country rather than be uniform, given variation in energy intensity, trade structure, and level of development. These implications were based on the direct findings of the CS-ARDL and are entirely consistent with the research's empirical findings.

Author Contributions

Adedeji Gbadebo contributed to this work through the conceptualization of the study, the drafting and critical analysis of the content, and the comprehensive editing of the manuscript.

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Conflicts of Interest

No conflict of interest.

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