Renewable Energy Consumption, Economic Growth, and Environmental Sustainability in Nigeria

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Received: 31 Aug 2026; Accepted: 01 Sept 2026; Published: 12 September 2026

ABSTRACT

This paper re-examines the Energy-Led Growth Hypothesis and the Environmental Kuznets Curve (EKC) for Nigeria by jointly modelling renewable energy consumption, real output, and carbon dioxide (CO_2) emissions. Annual observations for 1990-2025 are used exclusively to provide historical and contextual background, whereas the econometric analysis uses quarterly observations from 2010Q1-2025Q4. The estimated model is an augmented EKC specification in which the logarithm of CO_2 emissions is explained by the logarithm of real GDP, the square of logged real GDP, renewable energy consumption, gross fixed capital formation, and labour force. The ARDL bounds-testing framework is used to model quarterly dynamics and test for a levels relationship. Augmented Dickey-Fuller tests indicate that all five model series are I(1). The reported bounds F-statistic of 0.4349 is below the lower critical bound, so the null hypothesis of no long-run levels relationship cannot be rejected. Accordingly, the paper does not interpret the estimated short-run coefficients as evidence of stable long-run effects, and it does not claim a conventional long-run EKC. Instead, the results are interpreted as evidence of strong emissions persistence and short-run renewable-energy dynamics within the 2010Q1-2025Q4 estimation window. The paper concludes that Nigeria's renewable transition has not yet generated econometric evidence of a stable long-run growth-emissions-renewable-energy relationship and discusses the institutional conditions needed for a deeper transition.

Keywords: Renewable energy consumption; Economic growth; CO_2 emissions; Environmental Kuznets Curve; ARDL bounds testing; Nigeria

JEL Classification: Q42 (Alternative Energy Sources); Q43 (Energy and the Macro-economy); Q56 (Environmental and Sustainable Development); O13 (Economic Development: Agriculture, Natural Resources, Energy, Environment); O55 (Economic Development: Africa); C22 (Time-Series Models: Single Equations)

INTRODUCTION

Background

The global energy paradigm is undergoing a fundamental transformation, shifting away from the carbon-dependent fuels that underpinned industrial history toward more sustainable alternatives. Energy functions as the essential circulatory system of any economy, supplying the foundational power required for industrial productivity, wealth creation, and improved living standards (Beghabo, 2017 [1]). Yet the continued dependence on fossil fuels oil, coal, and gas has produced a twofold crisis: recurring macroeconomic instability driven by commodity-price volatility, and an accelerating environmental emergency manifested in ecological degradation and climate change (Ajayi et al., 2022 [2]). Consequently, the dominant global policy concern of the twenty-first century has become decoupling economic advancement from carbon emissions, in line with international climate commitments (IRENA, 2020 [3]).

For Nigeria, this transition carries particular urgency. Despite its standing as Africa's leading oil producer, the country suffers from severe energy poverty: chronic power-supply disruptions constrain industrial output, and a substantial share of the population remains without reliable access to electricity (Sylvester, 2026 [4]; Nwafor & Igwe, 2022 [5]). The continued reliance on traditional biomass for household energy is itself a symptom of energy scarcity rather than a deliberate shift toward cleaner fuels (Oloruntuyi, 2026 [6]). Against this backdrop, the relationship among renewable energy consumption, economic output, and CO2 emissions constitutes a first-order empirical question for Nigerian policy design. This study investigates how Nigeria might harness its substantial solar, hydro, and wind endowments to support economic growth while containing the environmental costs of its fossil-fuel-dependent energy system.

The academic literature on the Energy-Led Growth Hypothesis (ELGH) offers instructive, if not fully settled, guidance. Xie et al. (2022) [7] document a robust positive association between renewable energy deployment and economic progress across a panel of emerging economies. Nigeria-specific evidence broadly corroborates this pattern: using ARDL methods, Sylvester (2026) [4] reports that renewable energy consumption supports long-run GDP growth, while carbon emissions are inversely related to sustainable performance. Musa (2026) [8] extends this by highlighting ancillary benefits of the renewable transition, including employment generation and reduced operating costs for small and medium enterprises. Olusanya (2026) [9], however, cautions that much of this literature omits potentially confounding variables energy efficiency, private-sector participation, and external economic shocks that could materially alter the estimated energy growth relationship.

This study contributes to closing that gap by offering a rigorous econometric examination of the renewable energy-growth-emissions nexus in Nigeria, combining an explicit test of the EKC hypothesis with an assessment of the short- and long-run dynamics that link energy policy instruments to environmental outcomes. In doing so, it aims to furnish a more holistic, data-driven road-map for the policymakers and private investors navigating Nigeria's energy transition.

Nigeria possesses considerable untapped renewable energy potential extensive solar irradiation, substantial hydroelectric capacity, and viable wind resources in select corridors yet remains paradoxically tethered to a carbon-intensive energy model. As of 2026, the domestic energy sector continues to be hampered by chronic grid instability, pervasive energy poverty, and entrenched dependence on fossil fuels, a configuration that simultaneously fuels macroeconomic fragility and accelerates environmental degradation (Bloomfield Law, 2026 [10]; Aluko & Oyebode, 2026 [11]). Although the federal government has articulated strategic frameworks such as the 2060 Energy Transition Plan (ETP), a persistent "delivery gap" separates policy intent from implementation on the ground (Templars, 2026 [12]; SweetCrudeReports, 2026 [13]).

This challenge manifests along three interlocking dimensions. First, an economic barrier rooted in deep reliance on fossil fuels: inefficient domestic refining and costly fuel importation strain the national treasury and foreign-exchange reserves, with knock-on effects for long-run development (Bloomfield Law, 2026 [10]). Second, environmental deterioration: gas flaring and deforestation intensify greenhouse-gas emissions, with adverse consequences for public health and agricultural viability (SweetCrudeReports, 2026 [13]). Third, an institutional implementation deficit: despite progressive legislative reforms the Petroleum Industry Act (2021) and the Electricity Act (2023) the failure to cultivate an investment climate capable of attracting private capital leaves renewable initiatives fragmented and insufficiently scaled to meet national energy needs (Aluko & Oyebode, 2026 [11]).

Nigeria therefore confronts an urgent empirical and policy dilemma: how to reconfigure its energy infrastructure toward renewable sources in a manner that supports economic development while reducing its ecological footprint. Absent a rigorous, data-driven understanding of how renewable energy adoption, economic growth, and environmental sustainability interact within the Nigerian context, the country risks converting a resource endowment into stranded potential rather than inclusive development.

The overarching objective of this study is to investigate the dynamic interplay between renewable energy consumption, economic expansion, and environmental sustainability in Nigeria. Specifically, the study examines the short- and long-run effects of renewable energy consumption on CO2 emissions in Nigeria within an augmented Environmental Kuznets Curve framework, and tests the validity of the Energy-Led Growth Hypothesis by assessing the relationship between real output and CO2 emissions. It further seeks to determine whether Nigeria's growth-emissions relationship exhibits the inverted-U pattern predicted by the Environmental Kuznets Curve, and to evaluate the roles of capital formation and labour force size as scale-effect controls in the emissions equation. Finally, the study derives data-driven policy recommendations for closing the institutional "delivery gap" between Nigeria's energy-transition policy architecture and its practical implementation.

This study is guided by five research questions. First, what are the short-run and long-run effects of renewable energy consumption on CO2 emissions in Nigeria? Second, does Nigeria's economic growth-emissions trajectory conform to the inverted-U relationship predicted by the Environmental Kuznets Curve? Third, is there empirical support for the Energy-Led Growth Hypothesis in the Nigerian context over the study period? Fourth, do capital formation and labour force size exert the scale effects on emissions predicted by the augmented neoclassical growth framework? Fifth, is there a stable long-run (co-integrating) relationship linking emissions, output, renewable energy, capital, and labour in Nigeria?

The following hypotheses, stated in null form, are tested. H01 posits that renewable energy consumption has no significant effect on CO2 emissions in Nigeria. H02 posits that there is no inverted-U (Environmental Kuznets Curve) relationship between real output and CO2 emissions in Nigeria. H03 posits that there is no significant long-run (co-integrating) relationship among CO2 emissions, real output, renewable energy consumption, capital formation, and labour force.

This study advances the literature in three respects. First, rather than treating institutional quality and energy access as peripheral controls, it situates them within a coherent Ecological Modernization framework, evaluating explicitly whether Nigeria's most recent reforms the Electricity Act (2023) and the Energy Transition Plan are translating into measurable shifts in the energy-growth-emissions nexus. Second, it applies the ARDL bounds-testing procedure, which remains the most defensible estimator for small-sample, mixed-order-of-integration macroeconomic data of the kind available for Nigeria, thereby avoiding the pre-testing biases that can arise from imposing a common integration order across variables. Third, it reports its findings including a null result on long-run co-integration transparently, using that null result itself as diagnostic evidence of the shallowness of Nigeria's renewable energy penetration, rather than selectively emphasizing only statistically significant short-run coefficients.

The study uses annual 1990-2025 observations for historical context, while the econometric estimation is conducted exclusively on quarterly observations from 2010Q1-2025Q4. The remainder of the paper is organized as follows. Section 2 reviews the conceptual, theoretical, and empirical literature and identifies the research gap. Section 3 sets out the data, model specification, and econometric strategy. Section 4 presents and discusses the empirical results. Section 5 develops the economic intuition and policy implications of the findings. Section 6 concludes and offers policy recommendations, limitations, and directions for future research.

LITERATURE REVIEW

Conceptual Clarification

Understanding Nigeria's renewable energy transition requires clarifying several interlinked concepts. Renewable energy consumption refers to the share of final energy demand met from replenish-able sources solar, hydro, wind, and biomass as distinct from finite fossil fuels; Beghabo (2017) [1] frames energy broadly as the circulatory system of economic activity, underscoring why its composition matters as much as its volume. Economic growth, in this context, is measured through real output expansion, while environmental sustainability denotes development that meets present energy needs without compromising long-run ecological capacity, in line with global decoupling objectives (IRENA, 2020) [3]. Together, these framing works [1-3] establish energy, growth, and sustainability as the three conceptual pillars of the present study.

A further distinction concerns energy poverty versus a genuine renewable transition. Sylvester (2026) and Nwafor and Igwe (2022) [4,5] both note that unreliable grid access, not deliberate clean-energy substitution, still drives much of Nigeria's energy mix, while Oloruntuyi (2026) [6] cautions that continued biomass dependence reflects scarcity rather than a deliberate low-carbon shift. Ajayi et al. (2022) [2] link this pattern to a twofold macroeconomic and environmental crisis, in which commodity-price volatility and ecological degradation reinforce one another.

Two further concepts anchor the empirical strategy that follows. The Energy-Led Growth Hypothesis, first advanced by Kraft and Kraft (1978) [14], holds that energy consumption is a direct causal input to output growth rather than a mere by-product of it. The Auto-regressive Distributed Lag bounds-testing procedure of Pesaran, Shin, and Smith (2001) [15] is introduced here as the conceptual tool for detecting a stable long-run relationship among variables that may be integrated of different orders, a technique whose full specification follows in Section 3.

Theoretical Review

Ecological Modernization Theory (EMT), advanced by Mol and Spaargen (2000) [16], argues that economic development and environmental protection can be jointly pursued through technological innovation and institutional reform rather than treated as inherently opposed; this theory forms the anchor framework for the present study, elaborated fully in Section 2.3. A closely related, narrower perspective treats energy consumption as a direct factor of production alongside capital and labour, implying that energy expansion contributes causally to output growth (Stern, 2011) [17].

The Environmental Kuznets Curve (EKC), originally proposed by Grossman and Krueger (1991) [18], models environmental degradation as rising with income during the early stages of industrialization before falling once a threshold level of development enables cleaner technology and stronger regulatory capacity an inverted-U relationship that this study tests directly for Nigeria in Section 3.

Two further theoretical strands inform the resource-management dimension of the study. Modern Portfolio Theory, applied to energy diversification by Bhattacharya et al. (2016) [19], explains why over-concentration in hydrocarbon resources exposes an economy to heightened fiscal and macroeconomic risk, favoring a diversified energy portfolio. Finally, the sustainable development framework articulated by the Brundtland Commission (1987) [20] frames the trade-off between meeting current energy needs and preserving inter-generational environmental equity, situating Nigeria's transition within a broader normative context of balancing present growth against future ecological capacity.

Theoretical Framework

This study is anchored in Ecological Modernization Theory (EMT), which holds that economic development and environmental protection can be jointly advanced through strategic technological innovation and institutional reform (Mol & Spaargen, 2000 [16]). For the Nigerian context between 2010 and 2025, EMT offers a relevant lens for the country's central challenge: pursuing industrialization while bypassing the carbon-intensive trajectories characteristic of earlier-industrializing economies. The framework is applied here through the concept of "technological leapfrogging" examining the ongoing, if incomplete, shift from an unreliable, fossil-fuel-dependent national grid toward a more decentralized renewable energy architecture, and evaluating whether the Electricity Act (2023) and the Energy Transition Plan are genuinely fostering this modernization.

The study advances beyond conventional growth models by treating Nigeria's trajectory toward macroeconomic stability and reduced CO2 emissions as contingent on the state's capacity to modernize its energy mix. The empirical strategy in Section 3 operationalises this framework directly: the EKC's quadratic income term tests whether growth alone can be expected to reduce emissions, while the renewable energy term tests EMT's central claim that deliberate technological substitution rather than income growth percent is the more proximate driver of emissions reduction.

Empirical Review

Stern (2011) [17] and Xie et al. (2022) [7] treat energy as a core production input, establishing a causal link between energy consumption and industrial output. Their reliance on national aggregate data, however, obscures the reality of energy poverty within Nigeria's substantial informal sector, leaving unresolved how decentralized, off-grid renewable adoption affects localized growth relative to grid-based supply. This study addresses that gap by explicitly incorporating renewable energy consumption alongside conventional growth and capital variables in a single estimating equation, rather than inferring energy effects from aggregate output data alone.

Grossman and Krueger (1991) [18] propose the inverted-U income-pollution relationship that Olusanya (2026) [9] locates Nigeria within, on the carbon-intensive "rising phase." A recurring weakness of this literature is its assumption of roughly linear technological progress, which understates the drag exerted by Nigeria's institutional implementation gap and by specific, spatially concentrated pollutants such as gas flaring. This study addresses the gap by testing the EKC's quadratic specification directly against Nigerian data, allowing the estimated coefficients rather than an assumed trajectory to reveal whether the country is in fact positioned on the rising or falling segment of the curve.

Mol and Spaargen (2000) [16] argue that institutional reform and technology can jointly align growth with environmental health, but Ajayi et al. (2022) [2] caution that this can rest on "normative optimism" that understates Nigerian implementation realities. A substantial gap separates legislative intent from the creation of an environment that genuinely attracts investors. This study speaks to that gap by treating the estimated relationship between renewable energy and emissions as an empirical test of whether EMT's optimistic premise currently holds in Nigeria, rather than assuming it does.

Bhattacharya et al. (2016) [19] and Oloruntuyi (2026) [6] apply Modern Portfolio Theory to show how hydrocarbon over-concentration generates fiscal vulnerability. This literature, while theoretically coherent, tends to abstract from Nigeria's specific grid and infrastructural constraints, which complicate diversification, and there remains conflicting evidence on the near-term cost-effectiveness of solar relative to thermal capacity. This study contributes by estimating the short-run dynamic response of emissions to renewable energy consumption using quarterly Nigerian data spanning the 2010-2025 reform period, offering a more time-resolved picture than the cross-country panels typically used in this literature.

The Brundtland Commission's (1987) [20] framework, as adapted for Nigeria by Sylvester (2026) [4], centers on inter-generational equity but is frequently operationalised at the macroeconomic level, with limited attention to the immediate survival needs of marginalized, off-grid populations. This study cannot fully resolve that measurement gap given data availability, but it flags energy poverty and the institutional implementation gap as conceptual variables meriting inclusion in future micro-founded extensions of the present macro model.

Summary and Research Gap

Taken together, the reviewed literature establishes plausible theoretical channels ELGH, EKC, EMT, MPT, and sustainable development theory linking renewable energy, growth, and emissions, and it offers encouraging, if geographically and methodologically heterogeneous, empirical evidence for several of these channels in Nigeria and comparable emerging economies. However, three gaps remain salient. First, much of the Nigeria-specific literature (e.g., Sylvester, 2026 [4]; Musa, 2026 [8]) reports long-run relationships without systematically subjecting the underlying series to bounds-testing diagnostics capable of rejecting co-integration, raising the possibility of over-stated long-run claims. Second, comparatively little work tests the EKC's quadratic specification jointly with a renewable energy term for Nigeria specifically, as opposed to cross-country panels. Third, the literature has not adequately reconciled optimistic EMT-based policy narratives with the institutional implementation gap that Aluko and Oyebode (2026) [11] and Olusanya (2026) [9] document. This study addresses all three gaps directly by estimating a jointly specified ARDL model, reporting the bounds test result transparently (including a null finding), and interpreting that null finding through the lens of the institutional implementation gap rather than treating it as merely a statistical footnote.

METHODOLOGY

Data Variables and Estimation Sample

The study adopts an ex post factor research design appropriate to macroeconomic time-series analysis. Two analytically distinct uses of the data are maintained throughout the manuscript. Annual observations covering 1990-2025 are used only for historical and contextual description of Nigeria's growth, energy, and environmental trajectory. These annual observations are not the econometric estimation sample, and the 1990-2009 annual observations do not enter the ARDL estimation. The econometric model is estimated exclusively with quarterly observations from 2010Q1 through 2025Q4. This quarterly window is selected because it brackets the period surrounding major energy-sector policy reforms, including the Petroleum Industry Act (2021), the Electricity Act (2023), and the 2060 Energy Transition Plan, while also providing the quarterly frequency required to examine short-run adjustment dynamics. The full quarterly window contains 64 calendar quarters; after the loss of the initial observation associated with the reported one-period lag structure, the estimation output contains 63 observations (2010Q2–2025Q4).

Table 1: Variable Definitions and Sources

Variable	Symbol	Definition	Source
Real GDP	RGDP	Constant 2015 US$	WDI
Renewable Energy Consumption	REC	% of total final energy consumption	IEA / WDI
CO2 Emissions	CO2	Metric tons per capita	WDI
Gross Fixed Capital Formation	GFCF (CAP)	% of GDP	WDI / CBN
Labour Force	LAB	Total labour force	WDI

Source: Author's compilation (2026), based on the World Development Indicators (WDI), International Energy Agency (IEA), and Central Bank of Nigeria (CBN) statistical bulletins. The annual 1990-2025 series are used for contextual description only; the ARDL estimation is based exclusively on quarterly 2010Q1-2025Q4 observations.

ARDL Model Specification

The empirical model is an augmented Environmental Kuznets Curve specification. Let $y_t = \ln(CO2_t)$, $g_t = \ln(RGDP_t)$, $r_t = \ln(REC_t)$, $c_t = \ln(CAP_t)$, and $l_t = \ln(LAB_t)$. The exact functional form of the conditional levels relationship is:

$$\ln(CO2_t) = \beta 0 + \beta 1 \ln(RGDP_t) + \beta 2[\ln(RGDP_{t)}]^2 + \beta 3 \ln(REC_t) + \beta 4 \ln(CAP_t) + \beta 5 \ln(LAB_t) + \varepsilon_t.$$

The quadratic term is the square of logged real GDP, $[\ln(RGDP_t)]^2$, rather than $\ln(RGDP_t^2)$. The conventional EKC prior is $\beta 1 > 0$ and $\beta 2 < 0$. Renewable energy consumption is expected to have $\beta 3 < 0$ if greater renewable penetration reduces emissions, while capital formation and labour are expected to have positive scale effects ($\beta 4$, $\beta 5 > 0$).

The variables have the following operational definitions. Real GDP (RGDP) measures real output at constant 2015 US dollars and is sourced from the WDI. Renewable energy consumption (REC) is measured as the percentage of total final energy consumption and is sourced from the IEA/WDI. CO2 emissions (CO2) are measured in metric tons per capita and are sourced from the WDI. Gross fixed capital formation (GFCF/CAP) is measured as a percentage of GDP and is sourced from the WDI/CBN. Labour force (LAB) is measured as the total labour force and is sourced from the WDI. The logarithmic transformation is applied to the continuous model variables as specified above; the quadratic income term is constructed from logged real GDP.

The corresponding unrestricted ARDL error-correction representation is written generally as:

$$\Delta y_t = \alpha 0 + \Sigma(i=1 \text{ to } p_1)\ \varphi_i\ \Delta y_{(t-i)} + \Sigma(j=1 \text{ to } 5)\ \Sigma(i=0 \text{ to } q_{j1})\ \theta_{ji}\ \Delta x_j,(t_{i)} + \lambda_y\ y_{(t-1)} + \Sigma(j=1 \text{ to } 5)\ \lambda_j\ x_j,(t_{-1}) + u_t,$$

where $x_j = \{g, g^2, r, c, l\}$. The reported final short-run results contain one lag of the dependent variable and one lag of each listed regressor, corresponding to the displayed one-period dynamic specification. Because the uploaded manuscript does not contain the original E-Views lag-order selection screen or work-file metadata, the information criterion and maximum lag considered cannot be verified from the available source and are not invented here. Before submission, the authors should insert the exact criterion and maximum lag directly from the original E-Views estimation record. This is the only item in the requested ARDL specification that cannot be established from the manuscript itself.

Estimation Procedure

Estimation proceeds in four stages. First, Augmented Dickey-Fuller (ADF) tests are applied to each model series in levels and first differences to establish the order of integration and to ensure that no variable is I(2). In the reported results, all five series are I(1). Second, the ARDL bounds-testing procedure of Pesaran, Shin, and Smith (2001) is applied to the quarterly 2010Q1-2025Q4 estimation sample. Although the final ADF results place all variables in the I(1) class, the ARDL framework is retained because it provides an explicit test for a levels relationship and a flexible finite-sample dynamic specification.

Third, the lag structure is selected before estimation of the final ARDL equation. The manuscript reports the resulting one-period lag structure in Table 6, but the underlying work file needed to identify the exact information criterion and maximum lag searched is not included with the source manuscript. Those two details must therefore be verified from the original estimation record rather than reconstructed retrospectively from the coefficient table. Fourth, model adequacy is assessed using the Breusch Godfrey LM test for serial correlation and the ARCH test for conditional heteroscedasticity. Because the bounds test does not establish co-integration, no long-run ARDL coefficients, conventional error-correction interpretation, FMOLS/DOLS long-run estimates, or long-run causal claims are reported as established results.

The ARDL model is estimated in unrestricted error-correction form for the CO2 equation:

$$\Delta\ln(CO2_t) = \alpha 0 + \Sigma\gamma_i\Delta\ln(CO2_{(t-i)}) + \Sigma\delta i\Delta X_{(t-i)} + \lambda 1\ln(CO2_{(t-1)}) + \lambda 2X_{(t-1)} + \mu_t$$

where X is the vector of regressors (RGDP, $RGDP^2$, REC, CAP, LAB), Δ is the first-difference operator, and the λ coefficients on the lagged levels form the basis of the bounds F-test. The null hypothesis is H0: $\lambda 1 = \lambda 2 = 0$ (no levels relationship), against the alternative of a stable long-run levels relationship. If the F-statistic exceeds the upper bound, a levels relationship may be inferred; if it falls below the lower bound, the null of no levels relationship is not rejected; and if it lies between the bounds, the result is inconclusive.

No Toda-Yamamoto, FMOLS, or DOLS estimates are presented as empirical results in this manuscript. Such procedures would require separately documented estimation and are therefore outside the reported evidence.

A Priori Expectations

Table 2: A Priori Expectations of Coefficient Signs

Variable	**Expected Sign**	**Economic Rationale**
ln(RGDP)	$\beta 1 > 0$	Early-stage industrial growth raises energy throughput and emissions (EKC rising phase).
$\ln(RGDP)^2$	$\beta 2 < 0$	Higher income enables cleaner technology and stronger regulation (EKC turning point).
ln(REC)	$\beta 3 < 0$	Renewable substitution for fossil fuels reduces emissions independently of income (EMT channel).
ln(CAP)	$\beta 4 > 0$	Capital deepening expands industrial capacity and associated energy use (scale effect).
ln(LAB)	$\beta 5 > 0$	A larger workforce is associated with greater aggregate production and energy demand (scale effect).

RESULTS AND DISCUSSION

Descriptive Statistics

Table 3: Descriptive Statistics of Model Variables (Logged Series)

Statistic	CO2	GDP	GFCF	LAB	REC
Mean	0.6461	-2.1360	-2.1360	2.2715	62.4998
Median	0.6568	-0.2096	-0.2096	2.2396	62.1855
Maximum	0.7274	8.0563	8.0563	2.7605	66.1235
Minimum	0.5516	-26.1392	-26.1392	1.8394	61.0827
Std. Dev.	0.0438	9.4410	9.4410	0.2935	1.1738

Source: Author's computation (2026), EViews output.

The descriptive statistics indicate that logged CO2 emissions are tightly distributed (standard deviation of 0.044 around a mean of 0.646), consistent with a series that changes gradually rather than abruptly a pattern typical of a structurally persistent pollutant stock. Renewable energy consumption (REC) likewise shows low dispersion (standard deviation of 1.17 around a mean of approximately 62.5), suggesting that the renewable share of final energy consumption has moved within a comparatively narrow band over the estimation period rather than expanding rapidly, a first indication consistent with the institutional implementation gap discussed in Section 2 that Nigeria's renewable transition has been gradual rather than trans-formative. The GDP and GFCF columns are identical in the reported output; this duplication most plausibly reflects a transcription artefact in the underlying E-Views work file (for example, a copied variable definition) rather than a genuine economic equivalence between output growth and capital formation, and it is flagged here so that the original data file can be verified before further use. The wide range of the GDP/GFCF series (from -26.14 to 8.06) signals substantial volatility in growth and investment over the sample, plausibly reflecting the oil-price shocks, currency devaluations, and subsidy-reform episodes that characterized the Nigerian macro-economy across 2010-2025.

Unit Root (Stationarity) Test Results

Table 4: Augmented Dickey-Fuller (ADF) Unit Root Test Results

Variable	Level t-Stat	Level Prob	1st Diff. t-Stat	1st Diff. Prob.	Order of Integration
CO2	-0.6726	0.8457	-8.2999	0.0000	I(1)
GDP	-2.6396	0.0906	-7.7572	0.0000	I(1)
GFCF	-2.6291	0.0926	-5.5890	0.0000	I(1)
LAB	-0.1394	0.9394	-6.6149	0.0002	I(1)
REC	-2.1707	0.2188	-7.7465	0.0000	I(1)

Source: Author's computation (2026). Critical values (constant): -3.54 (1%), -2.91 (5%), -2.59 (10%), following MacKinnon (1996) [22].

None of the five series is stationary in levels: each ADF statistic is smaller in absolute value than the relevant critical value, so the null hypothesis of a unit root cannot be rejected at level for any variable. Once first-differences, however, all five series reject the unit-root null comfortably at the 1 percent level (or better), indicating that each variable is integrated of order one, I(1). Although this places all variables in the same integration class which would in principle permit a standard Engle-Granger or Johansen co-integration test the

ARDL bounds-testing approach is retained because it remains valid under this configuration and additionally accommodates any variable that might prove I(0) once model-specific lag structures are imposed, without requiring the researcher to pre-commit to a single integration order across the whole system.

ARDL Bounds Test for a Long-Run Levels Relationship

The bounds test is estimated on the quarterly 2010Q1-2025Q4 sample only. The annual 1990-2025 observations are contextual data and should not be described as part of the econometric sample. The choice of 2010Q1-2025Q4 reflects the need to capture quarterly dynamics around Nigeria's recent energy-sector reform period, including the Petroleum Industry Act (2021), the Electricity Act (2023), and the 2060 Energy Transition Plan, while retaining a sufficiently long quarterly window for ARDL estimation.

Test Statistic	Value	Significance	I(0) Bound	I(1) Bound
F-statistic	0.4349	10%	1.90	3.01
k = 4		5%	2.26	3.48
Sample size = 63		2.5%	2.62	3.90
		1%	3.07	4.44

Source: Author's computation (2026), based on Pesaran, Shin & Smith (2001) [15] asymptotic critical value bounds (n = 1000).

Source: Author's computation (2026), based on the reported ARDL output. Annual 1990–2025 observations are used for contextual description; the ARDL estimation uses quarterly 2010Q1–2025Q4 observations.

The quadratic specification is used to formulate the EKC hypothesis, but the bounds test determines whether that levels relationship is supported by the data. The exact functional form is:

$$\ln(CO2_t) = \beta0 + \beta1 \ln(RGDP_t) + \beta2[\ln(RGDP_t)]^2 + \beta3 \ln(REC_t) + \beta4 \ln(CAP_t) + \beta5 \ln(LAB_t) + \varepsilon_t.$$

The EKC prior is $\beta1 > 0$ and $\beta2 < 0$. However, because the bounds test reported below does not establish a long-run levels relationship, the coefficients in this levels equation cannot be interpreted as estimated long-run elasticities or as evidence of a stable long-run EKC.

The short-run ARDL estimates in Table 6 are therefore interpreted as dynamic conditional associations within the quarterly estimation equation. The lagged dependent variable is highly significant (0.9321, $p < 0.001$), indicating strong persistence in quarterly CO2 emissions. REC is positive and significant contemporaneously (0.006792, $p = 0.0020$) and negative and significant at one lag (-0.005690, $p = 0.0087$). These offsetting coefficients describe short-run timing effects; they do not establish a permanent emissions effect. LAB likewise changes sign across the contemporaneous and one-period lag terms, whereas GDP and GFCF are statistically insignificant at both reported horizons.

Table 6: ARDL Short-Run Estimates (Dependent Variable: CO2)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
CO2(-1)	0.9321	0.0649	14.3695	0
GDP	0.00011	0.00025	0.4522	0.653
GDP(-1)	-0.0002	0.00023	-0.7397	0.4627
GFCF	-6E-05	0.00023	-0.2631	0.7935

GFCF(-1)	-8E-05	0.00025	-0.3009	0.7647
LAB	-0.1838	0.0442	-4.1562	0.0001
LAB(-1)	0.1726	0.0465	3.7157	0.0005
REC	0.00679	0.00209	3.2446	0.002
REC(-1)	-0.0057	0.00209	-2.7216	0.0087

Model summary: $R^2 = 0.9587$; Adjusted $R^2 = 0.9526$; S.E. of regression = 0.0093; Durbin-Watson statistic = 1.9501; included observations = 63 (2010Q2–2025Q4).

Source: Author's computation (2026), EViews ARDL output.

The short-run ARDL results remain economically informative, but they are not evidence of a long-run equilibrium because the bounds test does not support co-integration. The model reports $R^2 = 0.9587$ and adjusted $R^2 = 0.9526$, indicating a high in-sample fit, while the interpretation of individual coefficients focuses on quarterly dynamics rather than structural long-run effects.

First, the lagged dependent variable, CO2(-1), carries a large, highly significant coefficient of 0.932. This confirms strong persistence in Nigeria's emissions path: the bulk of any quarter's emissions level is simply carried over from the previous quarter, consistent with the physical reality that a national energy and industrial infrastructure power plants, refineries, vehicle stock, gas-flaring sites cannot be reconfigured quickly. This persistence is precisely why a durable reduction in emissions requires a sustained, multi-year shift in the underlying energy mix rather than a single policy announcement.

Second, renewable energy consumption (REC) enters with a positive and significant contemporaneous coefficient (0.0068, $p = 0.002$) and a negative and significant coefficient at one lag (-0.0057, $p = 0.009$). The difference in signs suggests an offsetting short-run response across adjacent quarters. The coefficients should not be interpreted as evidence that renewable energy structurally increases emissions on impact or permanently reduces them after one quarter; the model does not establish such long-run claims.

Third, the labour force variable displays an analogous sign reversal: positive persistence effects aside, LAB carries a significant negative contemporaneous coefficient (-0.184, $p = 0.0001$) and a significant positive coefficient at one lag (0.173, $p = 0.0005$). One interpretation consistent with Nigeria's structural context is that short-run labour force expansions are concentrated in services and informal, low-energy-intensity activity, which does not immediately raise emissions and may even coincide with reallocation away from more energy-intensive sectors, but that the subsequent period brings the energy demand associated with expanded aggregate activity housing, transport, and consumption into the emissions series with a lag.

Fourth, output (GDP) and capital formation (GFCF) are statistically insignificant at both the contemporaneous and one-period lag in the short-run model (all p-values above 0.45). This does not necessarily indicate that growth and investment are irrelevant to Nigeria's emissions profile; rather, it suggests that, within a single quarter, changes in aggregate output and capital formation are too diffuse, or too heavily mediated by the existing (largely fossil-fuel) energy infrastructure, to register a statistically distinguishable short-run effect on emissions once the highly persistent CO2(-1) term and the more energy-specific REC and LAB variables are already included in the model.

Post-Estimation Diagnostics

Table 7: Post-Estimation Diagnostic Tests

Test	**F-Statistic**	**Prob. F**	**Obs*R-squared**	**Prob. Chi-Square**
ARCH (Heteroskedasticity)	0.6332	0.4293	0.6475	0.421

Breusch-Godfrey Serial Correlation LM	0.0399	0.9609	0.0965	0.9529

Source: Author's computation (2026), E-Views diagnostic output.

Both diagnostic tests fail to reject their respective null hypotheses: the ARCH test gives $p = 0.4293$, while the Breusch-Godfrey LM test gives $p = 0.9609$. These results indicate no detected conditional heteroscedasticity or serial correlation in the reported residual diagnostics. They support the adequacy of the reported short-run dynamic specification, but they do not compensate for the absence of evidence of a long-run levels relationship.

The hypotheses must be interpreted in light of the failure to establish co-integration. For H01, the reported coefficients provide evidence of statistically significant short-run responses of CO_2 emissions to REC, with opposite signs across the contemporaneous and one-period lag terms; thus, the null of no short-run REC effect is not supported, but this result should not be generalized to a stable long-run emissions effect. For H02, the absence of a supported levels relationship means that the present ARDL bounds-testing exercise does not establish a conventional long-run EKC. The signs of the quadratic income terms, if examined in the dynamic equation, cannot by themselves confirm an inverted-U long-run trajectory. H03 is directly supported by the bounds-test outcome: the null of no long-run levels relationship is not rejected over the 2010Q1-2025Q4 estimation window.

Accordingly, the manuscript's central empirical conclusion is deliberately narrower than a claim that Nigeria either has or does not have an EKC. The evidence indicates strong emissions persistence and statistically significant short-run renewable-energy dynamics, but no statistical support for a stable long-run growth-emissions-renewable-energy equilibrium within the specified sample and model. A stronger test of the EKC would require a specification and identification strategy that can establish the income-emissions relationship without relying on an unsupported long-run levels equation.

These findings qualify, rather than overturn, the theoretical frameworks reviewed in Section 2. The Energy-Led Growth Hypothesis and Ecological Modernization Theory both anticipate that a sufficiently deep renewable transition can durably reshape the growth emissions relationship; the present results suggest that Nigeria's renewable transition, as of the 2010-2025 window, has not yet reached the depth or persistence required to produce that durable reshaping, a conclusion that dovetails closely with the institutional implementation gap documented in the qualitative and policy literature (Aluko & Oyebode, 2026 [11]; Olusanya, 2026 [9]; Templars, 2026 [12]).

ECONOMIC INTUITION AND POLICY IMPLICATIONS

The results in Section 4 tell a coherent economic story once the statistical findings are read alongside Nigeria's institutional context. At its core, the emissions series behaves like a slow-moving stock variable: the coefficient of 0.93 on $CO_2(-1)$ implies a shock to emissions decays at roughly 7 percent per quarter, so it would take more than two and a half years for even half of a given emissions shock to unwind absent further intervention. This persistence has a direct policy corollary: emissions-reduction policy in Nigeria should be judged over a multi-year horizon, not a single budget cycle, because the underlying capital stock of power plants, refineries, and vehicles turns over slowly.

The sign reversal on renewable energy consumption positive on impact, negative at one lag, and small in net magnitude is best understood through the economics of capacity addition under an unreliable grid. When new renewable capacity (for example, embedded solar or mini-grid hydro) is added to a system in which existing diesel and gas-fired backup capacity is not simultaneously retired, the immediate effect can be an increase in overall energy throughput and hence emissions, as previously unserved or under-served demand is met by the combination of new and old capacity running in parallel. Only with a lag, as some of that legacy fossil capacity is displaced or under-utilized, does the substitution effect predicted by Ecological Modernization Theory begin to show through in the emissions data. The near-zero net effect found here (0.0068 - 0.0057) is the empirical signature of a transition that is underway but not yet self-sustaining precisely the condition described by the institutional implementation gap.

The absence of a long-run co-integrating relationship (Section 4.3) should not be read as a claim that renewable energy investment is economically futile in Nigeria. Rather, it is the econometric fingerprint of a renewable share that has moved within a narrow band (Table 3) rather than expanding to a scale capable of altering the structural relationship between growth and emissions. For a long-run relationship to emerge in future data, the renewable share of final energy consumption would need to move persistently and materially not merely fluctuate within its historical range a threshold effect familiar from other emerging-market energy transitions, where co-integration between clean energy and emissions typically appears only after renewable cross a double-digit share of a modernized (not biomass-dominated) energy mix.

The insignificance of GDP and GFCF in the short-run equation carries its own intuition: Nigeria's growth process, as currently configured, is not tightly coupled to visible quarter-to-quarter changes in the emissions series, most plausibly because a large share of economic activity informal-sector trade, services, and non-energy-intensive agriculture is not strongly energy-dependent, while the energy-intensive segments of the economy (oil and gas extraction and refining, cement, and grid-dependent manufacturing) are comparatively small and are already captured by the persistence in CO2(-1) rather than by contemporaneous GDP movements. This reinforces the case, consistent with Ecological Modernization Theory, for treating energy-mix composition not aggregate output growth alone as the primary lever available to policymakers seeking to influence Nigeria's emissions trajectory.

From a policy standpoint, three implications follow directly from the empirical evidence. First, because the short-run REC effect is only weakly net-negative, policy should priorities retiring or reducing utilization of legacy fossil-fuel back-up capacity alongside new renewable capacity additions, rather than treating renewable deployment as a purely additive exercise; without deliberate displacement of legacy capacity, new solar or hydro investment risks running in parallel with, rather than in place of, existing emissions sources. Second, because emissions are highly persistent, policy credibility and consistency matter more than the size of any single intervention: sustained enforcement of the Electricity Act (2023) and steady implementation of the Energy Transition Plan over a multi-year horizon are more likely to shift the long-run relationship than large, one-off announcements. Third, because the institutional implementation gap not the absence of renewable resource potential appears to be the binding constraint, policy attention should focus on de-risking private investment (streamlined licensing, bankable power purchase agreements, and foreign-exchange hedging instruments for renewable IPPs) so that Nigeria's substantial solar, hydro, and wind endowments can be converted into installed, dispatched capacity at a scale sufficient to register in the macroeconomic data.

CONCLUSION AND RECOMMENDATIONS

This study examined the dynamic relationship between renewable energy consumption, economic growth, and CO2 emissions in Nigeria using an ARDL bounds-testing framework estimated on quarterly observations from 2010Q1-2025Q4, while annual 1990-2025 observations were used only for historical context. The ADF results indicate that all five model variables are I(1). The reported bounds F-statistic of 0.4349 is below the lower critical bound, so the evidence does not support a stable long-run levels relationship among CO2 emissions, output, renewable energy consumption, capital formation, and labour over the estimation window.

The principal empirical evidence therefore concerns short-run dynamics. CO2 emissions are highly persistent; REC has statistically significant but opposite-signed contemporaneous and one-period-lag coefficients; labour also exhibits a sign reversal across the reported horizons; and GDP and GFCF are not statistically significant in the short-run equation. These findings are informative about quarterly adjustment dynamics, but they should not be presented as stable long-run effects. In particular, the study does not confirm a conventional long-run EKC for Nigeria over 2010Q1-2025Q4. The absence of co-integration means that the quadratic income specification does not provide evidence of a stable inverted-U levels relationship within this ARDL framework.

Policy Recommendations

i. Pair new renewable energy capacity additions with an explicit plan to retire or reduce reliance on

ii. diesel and gas-fired back-up generation, so that clean capacity substitutes for, rather than merely supplements, fossil-fuel-based supply.

iii. Prioritise consistent, multi-year enforcement of the Electricity Act (2023) and the Energy Transition Plan over episodic policy announcements, given the high persistence of Nigeria's emissions process.

iv. Deepen de-risking instruments for private renewable investment bankable power purchase agreements, foreign-exchange hedging facilities, and streamlined licensing to close the institutional implementation gap between legislative intent and installed renewable capacity.

v. Expand modern (grid- and mini-grid-connected) renewable capacity beyond its current, largely biomass-dominated composition, since only a materially larger and more persistent renewable share is likely to generate a detectable long-run cointegrating relationship with emissions.

vi. Commission periodic re-estimation of the ARDL model as additional post-2023 reform data accumulate, to monitor whether continued policy implementation eventually produces the long-run relationship that the current sample does not yet support.

vii. Complement the macro-level energy-transition agenda with targeted energy-access programmes for informal-sector and off-grid households, addressing the energy-poverty dimension that the aggregate REC measure does not fully capture.

LIMITATIONS OF THE STUDY

Three limitations qualify the study's conclusions. First, the failure to detect a long-run co-integrating relationship precludes estimation of long-run elasticities or a formal test of the EKC's quadratic shape; the analysis is therefore necessarily more informative about short-run dynamics than about long-run structural relationships. Second, the identical descriptive statistics reported for GDP and GFCF in Table 3 suggest a possible data-entry or transcription issue in the source work-file that could not be independently verified within the scope of this study; readers relying on the descriptive statistics for purposes beyond illustrating series dispersion should first confirm the underlying series against the original WDI/CBN data. Third, the study's reliance on aggregate REC and CO2 measures, while standard in this literature, does not distinguish between traditional biomass and modern renewable capacity, a distinction that Section 5 suggests may be economically material to the muted short-run effect observed.

RESEARCH FOR FURTHER STUDY

Future work should dis-aggregate renewable energy consumption into traditional biomass and modern renewable (solar, wind, hydro) components, to test directly whether the composition rather than the aggregate volume of renewable consumption drives the muted net effect identified here. Extending the sample as further post-2023 reform data become available would also permit a fresh bounds test with greater statistical power, potentially revealing a long-run relationship that the current, comparatively short quarterly sample cannot detect. Finally, complementing the aggregate ARDL approach with sub-national or firm-level data on renewable investment and institutional quality would help isolate the specific channels through which the institutional implementation gap operates.

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