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EXPLORING THE ENERGY CONSUMPTION AND CARBON EMISSIONS NEXUS IN NIGERIA

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Abstract: This study investigates the intricate nexus between energy consumption and environmental quality in Nigeria, a country that is highly vulnerable to climate change. Focusing on the Sustainable Development Goals (SDGs), particularly goal 13 climate action,

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this study examined the effect of diverse fossil fuel sources on environmental quality measured by CO2 emissions. By unbundling the diverse energy sources and assessing their individual and interactive influence from 1990 to 2023 using the Environmental Kuznets Curve (EKC) framework, this study provides a nuanced understanding of the impact of diverse energy sources on carbon emissions. By applying the EKC framework, this study aims to determine whether the nexus between economic growth and environmental degradation in Nigeria follows a hypothesized inverted U-shape. Using the Autoregressive Distributed Lag (ARDL) model, this study contributes to the extant literature by exploring both the long- and short-run linkages between energy consumption and CO2 emissions and analyzing the ripple effects across diverse economic sectors. The findings reveal a complex link between energy consumption, economic growth, and CO2 emissions, which is consistent with the EKC hypothesis. Energy consumption stimulates economic growth and significantly influences emissions from transportation, industrial activities, urbanization, and residential/commercial services in Nigeria. This study concludes with actionable policy recommendations emphasizing the transition to green energy, stringent emission regulations, and investment in public transportation infrastructure to mitigate CO2 emissions and enhance environmental quality. These insights can assist policymakers in formulating targeted interventions for sustainable growth and ecological sustainability.

Keywords: CO2 emissions; energy consumption; Environmental Kuznets Curve; sustainable development goals, climate change, Nigeria.

JEL Codes: C13, D53, O13, O16, O44, P28, Q01.

1. Introduction

This study is anchored to the Sustainable Development Goals (SDGs), particularly Goals 7, 8, 13, and 17, which emphasize affordable and clean energy, decent work and economic growth, climate action, and partnerships for sustainable development. The 21st-century economic and financial activities have emerged as significant catalysts for climate change concerns (Dauda et al., 2021; Samuel et, al 2021). The diversity of human activities related to these SDGs negatively influences the environmental quality. Notably, the increase in global and Nigerian environmental awareness is attributed to key initiatives such as the establishment of the Nigerian Conservation Foundation (NCF) in 1980, enactment of the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act of 2007, adoption of the National Climate Change Policy and Response Strategy of 2012, and Nigeria's participation in the Paris Agreement of 2015. Aboagye (2019) and Ogede et al. (2023) convincingly argued that poor management of the ripple effects of economic, financial, and human activities on environmental quality could diminish economic resources and impede the realization of SDGs. The realization of Nigeria's 21st-century economic and financial stability anchors on industrialization, leading to a geometric increase in urbanization, subsequently resulting in heightened energy consumption, with various economic sectors, including the commercial and public services industry and residential sectors, primarily relying on fossil energy-based resources containing approximately 75% to 85% of carbon dioxide (CO_2) emitted from fossil energy consumption across these sectors (see Figures 1 and 2).

The surge in residential energy consumption can be accredited to the COVID-19 pandemic safety protocols, particularly lockdown measures, compared to other sectors, such as commercial and public services and industry. The pivotal role of energy in sectoral development and industrial innovation underscores its indispensable link to economic development (Samuel et al., 2021; Abner, 2023; Megbowon et al 2023; Udo et al 2024). As such, this study examines the energy consumption and carbon emissions in Nigeria within the framework of the Environmental Kuznets Curve (EKC) hypothesis. Specifically, it seeks to understand the individual and collective contributions of economic development, industrialization, and urbanization to CO_2 emissions, and whether there exists a turning point where environmental quality improves with economic industrialization in Nigeria. Renewable and non-renewable energy sources constitute two key sources of consumable energy globally. Renewable energy is a self-replenishing energy source that includes solar, wind, water (hydro), and biomass energy. The supply of these energy sources is inexhaustible and may be inaccessible at times, resulting in spasmodic electricity generation. Similarly, non-renewable energy sources are non-self-replenishing fossil fuels such as coal, natural gas, and derivatives of crude oil, which are readily available for energy generation on demand.

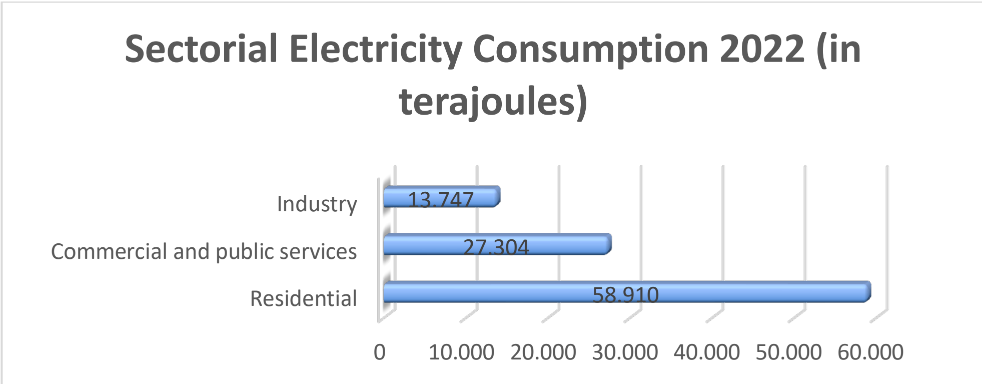

Figure 1 Sectorial Electricity Consumption 2022 (in Terajoules)
Sources: The authors' work based on data sources from the World Development Indicators (2023).

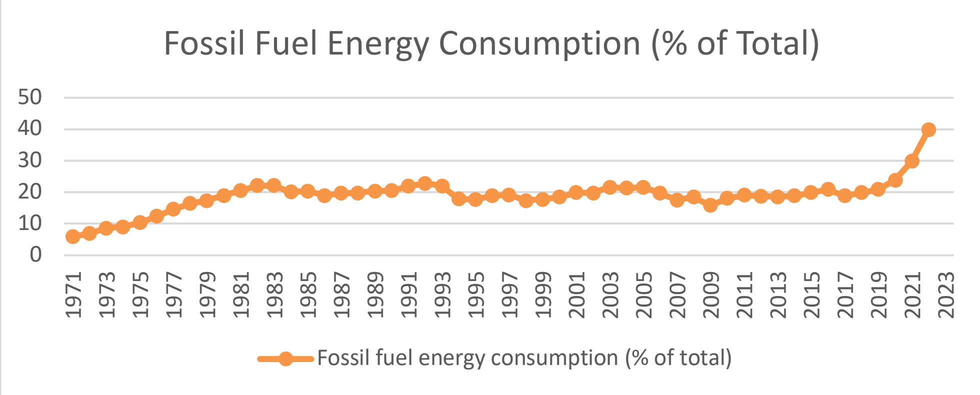

Figure 2 Fossil Fuel Energy Consumption (% of Total)
Sources: The authors' work based on data sources from the World Development Indicators (2023).

Udo et al. (2021), Abner et al. (2023), Abner et al. (2021), Ogwu et al. (2023), Inim et al. (2024), and others have linked environmental and natural resource depletion to deforestation and derivatives of crude oil-generated energy in emerging countries, such as Nigeria, which is among 7 of the 10 countries most vulnerable to climate change in Africa.

This study argues that against this lacuna, an in-depth empirical assessment is imperative to discern the energy consumption and environmental quality nexus in Nigeria. Furthermore, the ripple effect of economic activities through industrialization has not only simultaneously increased fossil energy consumption and diminished environmental quality but has also resulted in ocean acidification and air and water pollution, causing cardiovascular problems and impacts on marine life and biodiversity, thereby affecting agriculture and food security. Empirically, the hypothesized energy consumption and environmental degradation link necessitates a comprehensive analysis to ascertain whether energy consumption has a contributive influence on the escalation of ecological degradation as a result of Nigeria's heavy reliance on fossil fuels coupled with inadequate investment in renewable energy and policy frameworks to boost renewables, exacerbates climate change concerns in the country and jeopardized its capacity to achieve the SDGs, particularly those related to 7, 8, 13, and 17. (United Nations, 2015). Regardless of environmental concerns stemming from the heavy reliance on fossil fuels, there is a dearth of extant studies on the disaggregated levels of various sources of CO2 emissions in Nigeria, compared to studies in developed economies and others, to substantiate the EKC framework (Samuel et al., 2021; Odhiambo, 2017; Ogwu, et al 2023).

This study improves the literature on energy consumption and CO2 emissions by investigating the relationship between energy consumption and CO2 emissions. It also expands the frontier to analyze the ripple effect of diverse sources of fossil fuel consumption on environmental quality. The comprehensive disaggregation of the diverse sources of CO2 emissions deteriorating environmental quality is crucial for policymakers to formulate actionable targeted interventions. Extant studies in this context have often combined various fossil fuel sources, thereby hindering effective actionable policy formulation. Building upon the arguments of Lean and Smyth (2013), Samuel et al. (2021), Abner et al. (2021), Aboagye (2019), and Udoh et al. (2024), this study emphasizes the need for a nuanced analysis to elucidate the detailed drivers of ecological degradation in Nigeria and solve the lumping of various sources of fossil fuel consumption together in previous studies, thereby advancing the frontiers of extant studies. By focusing on bundled and unbundled analyses of the various energy consumption sources influencing CO2 emissions, an understanding of the individual interaction is crucial for addressing climate change concerns and achieving sustainable development goals through a targeted policy framework. By exploring the applicability of the EKC hypothesis in the Nigerian context, this study provides nuanced analyses of the instigators of environmental degradation in Nigeria and underlines the significance of understanding these dynamics for effective policy formulation and implementation to promote sustainable energy practices and environmental conservation in Nigeria.

2. Literature review

The extant empirical and theoretical literature has predominantly focused on assessing the contributive effect of environmental degradation in the context of economic and financial growth. Studies assessing energy consumption and environmental quality across diverse sources and income levels in Nigeria are limited. Kwakwa et al. (2018) observed that financial sector growth in Tunisia increased aggregate emissions from the transportation sector from 1971 to 2016. The findings of this study support the EKC hypothesis. Halliru et al. (2020) examined the financial sector growth and CO2 emissions nexus in six West African economies and found a U-shaped economic expansion and emissions nexus. This finding suggests that financial development and CO2 emissions have a negative relationship. Pata et al. (2021) observed a deviation from the Kuznets curve for human capital development, noting that a positive link between the human development index and green energy technology reduced CO2 emissions and improved environmental quality. In Malaysia, Ridzuan et al. (2020), Nigeria, Udoh et al. (2024), and MINT countries (Udo et al 2024) have collectively reported a link between economic growth, urbanization, and CO2 emissions. The results revealed that fossil fuel consumption diminished the environmental quality. Simultaneously, the adoption of green energy sources enhances environmental quality through eco-friendly economic growth and urbanization activities, supporting the EKC hypothesis. In Pakistan, Zhan et al. (2021) reported a positive association between renewable energy consumption and tourism, which improves environmental quality and holds for the EKC in Pakistan.

In 27 OECD economies, Alvarado et al. (2021) found a positive relationship between economic development and green energy sources, emphasizing the importance of incorporating human capital development and globalization indices to facilitate a sustainable energy mix. In the United States, Zafar, Zaidi, Khan, et al. (2019) observed that economic growth and energy consumption increased the ecological footprint from 1970 to 2015. Tang et al. (2021) reveal that institutional quality supports foreign direct investment (FDI) and renewable energy to improve environmental quality in 144 economies. Isık et al. (2019), Isik et al. (2021), Musakwa et al. (2022), Inim et al. (2024), and Ongan et al. (2022) validated the EKC hypothesis. The extant literature on energy consumption and carbon emissions in Nigeria offers valuable insights into the dynamics of environmental degradation amidst rapid economic development. However, there is a lack of consensus regarding the applicability of the EKC hypothesis in the Nigerian context.

Kwakwa et al. (2018), Neagu and Neagu (2022), Inim et al. (2024), and Halliru et al. (2020) support the EKC hypothesis, suggesting that environmental quality initially deteriorates before improving at higher income levels. The findings of Pata et al. (2021) challenge this notion, emphasizing the complexities of the nexus between economic growth and environmental degradation. This study aimed to fill this gap by reconciling these conflicting findings and providing a more nuanced understanding of the EKC dynamics in Nigeria. Previous literature has primarily focused on aggregate measures of energy consumption and carbon emissions, ignoring sector-specific contributions to environmental degradation. While studies have identified key sectors, such as transportation, industry, and residential/commercial services, as significant instigators of carbon emissions, there is a lack of comprehensive analysis regarding the drivers and impacts of emissions from these sectors. Addressing this gap will enable policymakers to develop targeted interventions to effectively mitigate emissions from the most polluting sectors for sustainable development.

2.1 Some Stylized Facts

This study holds significance in Nigeria, Africa's economic powerhouse, with a GDP of approximately 447.4 billion U.S. dollars in 2022-2023, surpassing South Africa's GDP of 405.7 billion U.S. dollars. Nigeria's economic and financial prosperity raises environmental concerns, particularly regarding fossil energy consumption for industrialization and the depletion of environmental quality. Nigeria's status as an oil-producing country with a daily production of about 1.67 million barrels per day and 44.3 million liters consumption per day underlines its carbon-intensive nature. The heavy dependence on fossil fuels for domestic energy production and exports further exacerbates its carbon footprint. In 2021-2022, Nigeria embittered approximately 136 million CO2 emissions, ranking 4th highest in Sub-Saharan Africa (SSA). The trajectory of Nigeria's daily CO2 emissions clearly demonstrated its environmental impact (See Figure 3). Sustained energy-related emissions can be accredited to the deliberate promotion of energy-intensive industries such as petroleum and petrochemicals, steel, cement production, fertilizer manufacturing, and aluminum smelting in the 1999 pre-democratic era to stimulate economic industrialization, exacerbating Nigeria's carbon footprint.

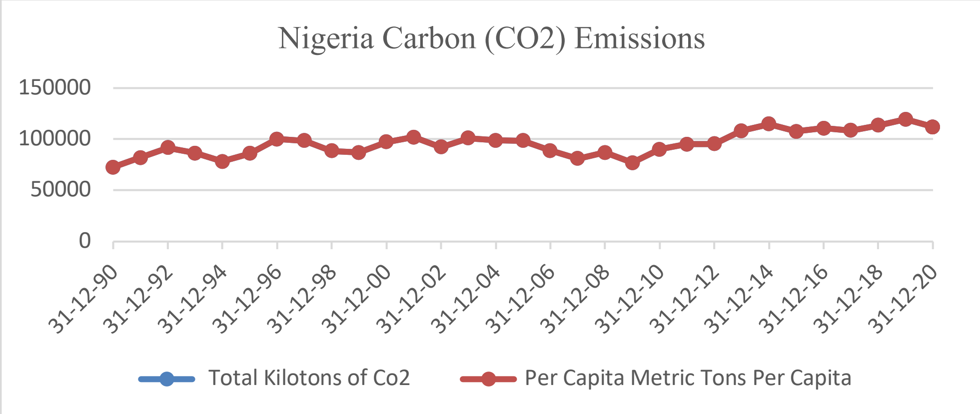

Figure 3 Nigeria Carbon (CO2) Emissions

Sources: The authors' work based on data sources from the World Development Indicators (2023).

Given Nigeria's sustained dependence on fossil fuels to bridge the energy demand-supply gap, a robust energy consumption and CO2 emissions policy framework is inevitable to ensure environmental sustainability. This implies that for every terajoule of energy consumers in Nigeria, ecological quality is depleted, rendering Nigeria vulnerable to climate change triggered by energy consumption (Abner et al. 2023). Energy consumption has emerged as a critical element of Nigeria's explanation of the Environmental Kuznets Curve (EKC) phenomenon.

3. Methodology

3.1 Theoretical Framework

Global warming and climate change have become fundamental global environmental issues in recent decades. Increasing kilotons of CO2 emissions remain a crucial stimulant of global warming and climate change emanating from the sectoral and human consumption of fossil fuels. This study comprehensively and in detail explores the contributive impact of various sources of CO2 emissions through energy consumption within the EKC framework in Nigeria. Understanding the interconnectedness of the diverse sources of CO2 emissions is decisive in developing a comprehensive model to estimate the energy-CO2 emission correlation and for policymakers to develop targeted strategies to mitigate the adverse effects on environmental quality to foster eco-friendly industrialization, urbanization, and economic expansion in Nigeria. The EKC framework reflects the Environmental Transition Hypothesis, which suggests that economies transition from reliance on natural resources to industrialization, and ultimately to a service-based economy, as they evolve. The framework aligns with the pollution-haven hypothesis, which posits that industries from environmentally straight nations relocate to countries with lax environmental regulations, increasing pollution levels during the early phases of industrialization. The incorporation of insights from neoclassical economics, emphasizing the role of technological innovation and environmental regulations in mitigating environmental degradation as economies mature, further provides the theoretical perspectives of this study.

EKC Framework

The effects of economic industrialization and urbanization on ecological quality were elucidated within the EKC framework developed by Grossman and Krueger (1995) in Nigeria. Grossman and Krueger's (1995) EKC hypotheses draw inspiration from Kuznets' (1955) income and inequality study, depicting an inverted U-shaped environmental indicator and per capita income nexus. The EKC framework indicates that in the short-run "pre-industrial phase,' economic industrialization depletes environmental quality due to emphasis on material output, income level, and lax regulatory attention on environmental concerns. In the long-run "post-industrial phase," as economic and income levels evolve in alignment with SDGs 7, 8, 13, and 17, regulatory institutions ensure straight eco-friendly activities, which indicates an inverted U-shaped nexus (See Figure 4). Theoretically, this underscores the need for increased emphasis on environmental quality, sustainable energy consumption, and development.

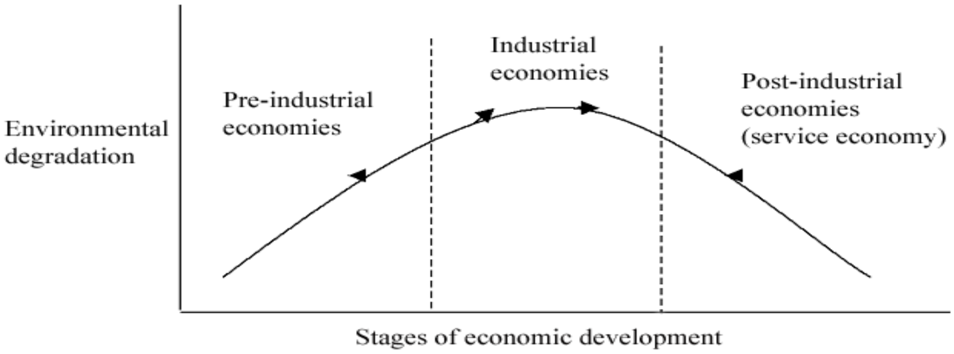

Figure 4 The shape of the EKC
Source: Panayotou (2003, p.46), as cited in Inim et al. (2024, p.79)

The EKC model traditionally embraces various environmental dilapidation indicators, such as per capita carbon (CO_2), sulfur (SO_2), nitrogen (NO_x), methane (CH_4), and ozone (O_3), as a function of per capita income levels and their squares. Harbaugh et al. (2002) and Panayotou (2003) argue that factors beyond income significantly influence environmental quality in the EKC model, potentially leading to spurious results. Multifaceted factors, including the size of the economy, sectoral configuration, technological innovations, environmental sustainability demand, and protection expenditures, influence economic growth and environmental quality. The EKC model offers a lens to analyze these dynamic linkages, recognizing the complexity of factors captured within the context of economic development.

The applicability of the EKC in Nigeria offers valuable insights into the environmental degradation trajectory during rapid economic development. Economic industrialization, driven by sectors such as manufacturing, transportation, and energy production, contributes to CO_2 emissions during the initial phases of development. Urbanization further exacerbates environmental degradation as population growth and infrastructure expansion place extra pressure on natural resources and ecosystems. As income levels increase, along with regulatory institutional reforms, the EKC reveals that Nigeria's environmental quality begins to improve.

Despite its heuristic value, the EKC framework has been heavily criticized for oversimplifying the economic growth and environmental degradation nexus and ignoring the complex socioeconomic factors and institutional dynamics that influence environmental effects. The EKC's reliance on aggregate economic indicators obscures disparities in environmental impacts across socioeconomic groups and geographical regions. Similarly, Shahbaz and Sinha (2019), Omri (2018), Cole (2004), Agras and Azoize (1996), Stern (2004), and Inim et al. (2024) argue that the EKC may not universally apply to all countries or environmental indicators. This study examined its applicability in the Nigerian context.

3.2 Data

The annualized time-series dataset was collated from the World Bank Indicators (2022) from to 1990-2023 (33-year period) in Nigeria. Employing an ex-post facto research design, energy consumption was evaluated based on unbundled and bundled sources, focusing on their contribution to economic growth and impact on environmental quality. The EKC model hypothesizes that the nexus between environmental degradation and economic growth follows an inverted U-shape. According to the EKC, in the initial phase of economic growth, economic agents prioritize output and development to the detriment of environmental quality, until reaching a certain growth threshold, is achieved, and societies can afford cleaner technologies and enforce stricter environmental regulations, thereby improving environmental quality. The basic EKC model is expressed in (Eq1).

Method

The EKC model is mathematically expressed as:

$CO_2 = \beta_0 + \beta_1 PGDP + \beta_2 PGDP^2 + \beta_3 PGDP^3 + \beta_4 X + \epsilon$………… (1).

Where CO_2 is carbon dioxide emissions, β_0 is the intercept; β_1-β_3 the coefficients of the nexus between PGDP and CO2 emissions.
β_1 = linear effect of PGDP on CO2 emissions.
β_2 = quadratic effect (turning point).
B_3= any cubic effect, allowing for more complex relationships.
X = vector of other control variables that may influence CO2 emissions.

The EKC hypothesis

$\beta_1 = \beta_2 = 0$: No linkage between CO2 and PGDP.
$\beta_1 > 0$ and $\beta_2 = 0$: the Linkage between CO2 and PGDP is linear.
$\beta_1 < 0$ and $\beta_2 = 0$: the Linkage between CO2 and PGDP is negative.
$\beta_1 > 0$ and $\beta_2 < 0$: The Linkage between CO2 and PGDP is "inverted U, " and the EKC is confirmed.
B_3 is included for more flexible modeling, to capture potential non-linear nexus beyond a simple quadratic form.
For the EKC hypothesis to hold, there must be an "inverted U" relationship between CO2 emissions and PGDP according to (Allard et al., 2018) which is calculated as $PGDP^* = -\frac{\beta 1}{2\beta 2}$

Iwata et al. (2012) argued that in developing countries in Nigeria, the turning points might fall outside the sample period, indicating that environmental depletion may continue to increase with economic growth in Nigeria. To test the EKC hypothesis in Nigeria, this study employed a reduced form of the EKC framework. Within the borders of this theoretical framework, we incorporated variables such as total natural resource rents, energy consumption, urban population, foreign direct investment, and net inflows to comprehensively assess their impact on environmental quality through the diverse sources of CO2 emissions, such as methane emissions, nitrous oxide emissions, solid fuel emissions, gaseous fuel emissions, liquid fuel emissions, and emissions from residential buildings and commercial and public services. The estimation framework developed with these variables provides a comprehensive analysis of their effects on environmental quality within the EKC context. The description of the study variables is presented in (Table 1). The linear specifications of the study are as follows.

$$In(CO2)_t + \beta_0 + \beta_1 In(ENCO)_t + \beta_2 InFDI_t + \beta_3 InTRO_t + \beta_5 InUBP_t + \beta_6 InPGDP_t + \beta_7 InPGDP^2{}_t + \beta_8 InNRR_t + \beta_9 InSRV_t + \beta_{10} InAGR_t + \beta_{11} InMAN_t + \beta_{12} InIND_t + \varepsilon_t \text{ …………(2)}$$

Where t = time; ε = white noise.

Adopting Panayotou's (1993) EKC model originally proposed by Grossman and Krueger (1991), this study uses squared income as an independent factor for environmental quality while incorporating additional exogenous parameters. Equation (1) shows the EKC based on the estimated income and economic growth coefficients.

Table 1 Variable Description

Variables	Symbols	Unit	Description
Carbon Emission	CO_2	Kt	CO2 emissions from solid, liquid, and gas fuels, gas flaring, and manufacturing contribute significantly to climate change and environmental degradation. CO2 emission in (Eq2), is assessed at the unbundled and bundled levels.
Unbundled CO2 Emissions Indicators			
Methane	MEE	CH_4	Emanate from transmission and automobile combustion of fossil fuels and biofuels.

Nitrous oxide	NOE	N_2O_e	Emissions arising from agricultural biomass burning, industrial activities, fertilizer use, animal waste management, savanna burning, and livestock management.
Solid fuel	SFE	SF_{CO2e}	Solid fuel emissions come from the use of coal.
Gaseous fuel	GES	GF_{CO2e}	% of total fuel combustion
Liquid fuel	LFE	LF_{CO2e}	Liquid fuel emission comes from the consumption of petroleum-derived fuel.
Emissions from residential buildings and commercial and public services	RBCPS	RB_CPS_{CO2e}	% of total fuel combustion)
GDP per capita growth	PGDP	Constant US$ 2015	Economic growth increases energy consumption and industrial output, leading to higher emissions in the initial stages of development.
Total natural resources rents	NRR	(% of GDP	It is the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents.
Foreign direct investment, net inflows	FDI	(% of GDP)	FDI inflows, including equity, reinvested earnings, long-term and short-term capital, resulting in high emissions.
Energy Consumption	ENCO	(% of total Energy)	Measures level of energy consumption from fossil fuel sources of coal, oil, petroleum, and natural gas products.
Services, value-added	SRV	(% of GDP)	It denotes sectoral contribution to economic growth and influences environmental quality.
Agriculture, forestry, and fishing, value added	AGR		
Manufacturing, value added	MAN		
Industry (including construction), value-added	IND		
Urban population	UBP	(% of the total population)	Urban population, as a percentage of the total population, is influenced by

			industrialization and significantly impacts environmental quality.

Source: Author's work (2024) Based on data from the World Bank Indicators Database (2023) http://data.worldbank.org/data-catalog/world-development-indicators

3.3 Model Estimation

Unit Root

Before estimating the ARDL model, the stationarity properties of the series were tested to determine whether the series follows a stochastic trend using the first-generation unit test model of augmented Dickey (ADF) and Phillips-Perron (PP) to ensure that the series meets the Gauss-Markov conditions for unbiased estimation and to give credibility to our adopted estimation technique. The PP test, which is distinct from the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test, uses a nonparametric correction to the statistics, while assuming heteroscedastic white noise. This test assumes that the variables are either stationary at the I (0) level or at the I (1) first difference. The decision criterion is to reject the null hypothesis of unit roots if the ADF and PP statistics are higher than the critical value, or if the p-value is greater than 0.05.

The model expression: $\Delta y_{t-1} = \alpha_0 + \lambda_{yt-1} + \alpha_{2t} + \Sigma p$ i=2 $\beta_j \Delta_{yt-1} + \mu_t$.

where Y= dependent variable, t = trend, I = intercept, μ_t = white noise, and p =lag level.

Hypothesis:

H_0: there is a unit root.

H_1: there is no unit root.

Autoregressive Distributed Lag Model (ARDL)

We adopted the ARDL model developed by Pesaran et al. (2001) to estimate the long-run nexus between energy consumption, economic growth, and diverse sources of CO2 emissions on environmental quality. Distinct from the traditional cointegration techniques, the ARDL model syndicates variables of diverse orders of integration (I(0) or I(1)) but not I(2), and controls for endogeneity and serial autocorrelation, which previous studies failed to address. This model is suitable for small sample sizes, whereas the traditional approaches are sensitive to small samples. The ARDL model is expressed as follows.

$$\Delta InCO2_t = \beta_0 + \sum_{i=1}^{p} \beta_i \Delta InCO2_{t-i} + \sum_{i=0}^{k1} \delta_i \Delta InENCO_{t-i} + \sum_{i=0}^{k2} \lambda_i \Delta InTRO_{t-i} + \sum_{i=0}^{k3} \Upsilon_i \Delta InUBP_{t-i} + \sum_{i=0}^{k4} \phi_i \Delta InPGDP_{t-i} + \sum_{i=0}^{k5} \phi_i \Delta InPGDP^2_{t-i} + \sum_{i=0}^{k6} \pi_i \Delta InNRR_{t-i} + \sum_{i=0}^{k7} \theta_i \Delta InSRV_{t-i} + \sum_{i=0}^{k8} \upsilon_i \Delta InAGR_{t-i} + \sum_{i=0}^{k9} \psi_i \Delta InMAN_{t-i} + \sum_{i=0}^{k10} \omega_i \Delta InIND_{t-i} + \sum_{i=0}^{k11} \tau_i \Delta InFDI_{t-i} + \varepsilon_t \quad \text{.........(3)}$$

The bound test was expressed as in (4):

$$\Delta InCO2_t = \beta_0 + \sum_{i=1}^{p} \beta_i \Delta InCO2_{t-i} + \sum_{i=0}^{k1} \delta_i \Delta InFDI_{t-i} + \sum_{i=0}^{k2} \lambda_i \Delta InTRO_{t-i} + \sum_{i=0}^{k3} \Upsilon_i \Delta IUBP_{t-i} + \sum_{i=0}^{k4} \phi_i \Delta InPGDP_{t-i} + \sum_{i=0}^{k5} \phi_i \Delta InPGDP^2_{t-i} + \sum_{i=0}^{k6} \pi_i \Delta InNRR_{t-i} + \sum_{i=0}^{k7} \theta_i \Delta InSRV_{t-i} + \sum_{i=0}^{k8} \upsilon_i \Delta InAGR_{t-i} + \sum_{i=0}^{k9} \psi_i \Delta InMAN_{t-i} + \sum_{i=0}^{k10} \omega_i \Delta InIND_{t-i} + \lambda_1 In\, CO2_{t-1} + \lambda_2 InENCO_{t-1} + \lambda_3 InFDI_{t-1} + \lambda_4 InTRO_{t-1} + \lambda_5 InUBP_{t-1} + \lambda_6 InPGDP_{t-1} + \lambda_7 InPGDP^2_{t-1} + \lambda_8 InNRR_{t-1} + \lambda_9 InSRV_{t-1} + \lambda_{10} InAGR_{t-1} + \lambda_{11} InMAN_{t-1} + \lambda_{12} InIND_{t-1} + \varepsilon_t \quad \ldots\ldots\ldots\ldots(5)$$

Where: Δ is the difference operator and ln = natural log of the variables.

The estimated F-statistic values were compared with the upper- and lower-bound critical values to determine the presence of a long-run nexus.
Decision rule: where F-statistics is (>) the upper critical value (cointegration); (<) upper and lower critical values (no cointegration); falls between the upper and lower critical values (inconclusive).
Λi captures the short-run dynamics in (5)
where i = 1, 2,3,4,5. . .9, and the long-run dynamics are captured by β_i, γ_i, δ, ρ_i, τ_i, υ_i, θ_i, ωi, ϕ_i, χ_i and σ_i for i = 1, 2, 3, 4, 5. . . ., p.

The Error Correction (ECT) model in (5) is expressed as:

$$\Delta InCO2_t = \beta_0 + \sum_{i=1}^{p} \beta_i \Delta InCO2_{t-i} + \sum_{i=0}^{p} \delta_i \Delta InENCO_{t-i} + \sum_{i=0}^{p} \lambda_i \Delta InTRO_{t-i} + \sum_{i=0}^{p} \Upsilon_i \Delta InUBP_{t-i} + \sum_{i=0}^{p} \phi_i \Delta InPGDP_{t-i} + \sum_{i=0}^{p} \pi_i \Delta InNRR_{t-i} + \sum_{i=0}^{p} \theta_i \Delta InSRV_{t-i} + \sum_{i=0}^{p} \upsilon_i \Delta InAGR_{t-i} + \sum_{i=0}^{p} \psi_i \Delta InMAN_{t-i} + \sum_{i=0}^{p} \omega_i \Delta InIND_{t-i} + \sum_{i=0}^{p} \tau_i \Delta InFDI_{t-i} + \infty ECT_{t-1} + \varepsilon_t \ldots\ldots\ldots\ldots (6).$$

ECT captures the long-run coefficient ∞ and measures the speed of convergence from the short-run divergence due to shocks in the system. ∞ was negative and significant after an external shock. Diagnostic tests for ECM results were conducted.

4. Empirical Estimation

Table 2 Basic Descriptive Statistics of the Variables

	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
AGR	24.282	23.893	36.965	19.990	3.710	1.607	6.153	27.894
CO2	95836.97	95335.30	119544.1	72768.80	12109.13	0.095	2.179	0.916
RBCPS	7.735	7.322	15.039	2.465	3.993	0.078	1.569	2.156
ENCO	19.347	18.876	22.844	15.854	1.750	0.322	2.372	0.842
FDI	1.318	1.380	2.900	-0.039	0.844	0.112	1.892	1.755

GES	17927.28	18067.31	32702.31	7484.347	8216.019	0.499	1.889	2.510
PGDP	1632.967	1871.756	3200.953	494.129	812.566	-0.015	1.833	1.872
IND	28.511	28.220	37.709	18.173	5.163	0.180	2.314	0.824
LFE	38695.68	33036.00	70120.37	22255.02	14625.84	0.950	2.430	4.434
MAN	12.759	11.811	20.927	6.552	4.452	0.400	1.746	3.040
MICE	9.406	9.667	13.968	4.249	2.635	-0.362	2.337	1.005
MEE	89134.38	90938.50	98880.10	71878.20	6822.360	-0.655	2.824	2.261
NOE	29703.60	29708.75	41196.30	20146.93	6482.453	0.273	1.954	1.798
SRV	46.202	44.684	59.785	35.358	6.151	0.287	2.460	0.853
SFE	0.086	0.081	0.252	0.0086	0.063	1.063	3.947	6.096
NRR	15.405	15.686	34.269	4.554	6.733	0.476	3.297	1.326
UBP	40.55542	39.943	53.521	29.680	7.558	0.1882	1.701	2.512

Source: Author's work based on E-Views 13 and data from the World Development Indicators (2023).

The results reported in Table 2 show the measures of central tendencies, including the mean, median, and standard deviation, which assess the spread and variation in the series. The skewness, kurtosis, and Jarque-Bera values indicate series normality. These findings highlight the significant influence of economic and industrial activities on energy consumption and CO2 emissions in Nigeria. The mean and median values of the AGR indicate a sectorial contribution of 24-25% economic industrialization. Agricultural activities deplete environmental quality in the short run, whereas sustainable practices enhance reforestation for long-term sustainability. The high mean and median values of (95,000-96,000 metric tons) indicate a significant carbon footprint associated with economic industrialization, energy production, transportation, and deforestation in Nigeria, underscoring the importance of addressing environmental concerns as a motivation for this study. Emissions from the RBCPS in Nigeria are moderate and evident in the mean median values of 7.73-7.32%. High energy consumption (ENCO) from fossil sources (mean median values of 19.34-18.87%) is driven by economic growth and industrialization. Positive mean and median values of Foreign Direct Investment (FDI) indicate significant inflows into Nigeria to support sustainable green energy development and environmental conservation efforts. The industrial sector's contribution to economic industrialization (mean and median values of 28-29%) indicates substantial energy consumption and CO2 emissions. Emissions from liquid and solid fuel consumption underscore the ripple effect on environmental quality, necessitating a transition towards green energy sources and technologies. The manufacturing sector's contribution to economic industrialization (mean and median values of 12-13%) indicates an increase.

3.2 Unit Root Test

The stationarity properties of the series were assessed and determined using the ADF and PP unit root test models. This test enabled us to meet the Gauss-Markov conditions for unbiased estimation and eliminate biased results. As previously cited, along with the decision rule for accepting and rejecting the null hypothesis of the unit root. The test results presented in Table 3 show that the series is stationary at diverse orders of integration I(0) and I(1) at the 5% and 10% critical levels, following the ADF and PP test results. The unit results theoretically underpinned the adoption of the Pesaran Shin and Smith (2001) ARDL bound test model to investigate the cointegrating energy consumption and CO2 emission nexus in Nigeria.

Table 3 Unit Root Test ADF and PP Results

Variables	Test	I (0) level	Inference	Test	I (1) 1st Difference	Inference
Trend and Intercept						
CO_2	ADF	-2.772 (0.217)	Non-Stationary	ADF	-5.491 (0.006)	Stationary
	PP	-2.772 (0.217)		PP	-6.192 (0.001)	
MEE	ADF	-2.502 (0.325)	Non-Stationary	ADF	-6.233 (0.002)	Stationary
	PP	-2.296 (0.422)		PP	-10.333(0.000)	
NOE	ADF	-3.134 (0.116)	Non-Stationary	ADF	-6.523 (0.000)	Stationary
	PP	-2.253 (0.444)		PP	- 8.3900 (0.000)	
SFE	ADF	-3.029 (0.144)	Non-Stationary	ADF	-5.277 (0.001)	Stationary
	PP	-4.223 (-3.595)		PP	5.766(0.004)	
MICE	ADF	-5.195 (0.002)	Stationary	ADF	-3.001 (0.152)	Non-Stationary
	PP	-12.499 (0.000)		PP	-2.965 (0.161)	
GES	ADF	-3.417 (0.0715)	Non-Stationary	ADF	-4.900 (0.003)	Stationary
	PP	-2.921 (0.172)		PP	-7. 892 (0.000)	

LFE	ADF	-2.599 (0.297)	Non-Stationary	ADF	-5.557 (0.007)	Stationary
	PP	-2.534 (0.310)		PP	-8.170 (0.000)	
RBCPS	ADF	-4.037 (-3.612)	Non-Stationary	ADF	-6.569 (0.001)	Stationary
	PP	-4.107 (0.019)		PP	15.930 (0.000)	
PGDP	ADF	-2.093 (0.529)	Non-Stationary	ADF	-4.954 (0.0025)	Stationary
	PP	-2.265 (0.439)		PP	-4.909 (0.002)	
NRR	ADF	-6.977(0.000)	Stationary	ADF	-4.977 (0.421)	Non-Stationary
	PP	13.999 (0.000)		PP	-4.210 (0.0119)	
FDI	ADF	-2.005 (0.565)	Non-Stationary	ADF	-6.631 (0.000)	Stationary
	PP	-2.403 (0.370)		PP	-6.947 (0.000)	
ENCO	ADF	-2.441 (0.351)	Non-Stationary	ADF	-4.909 (0.003)	Stationary
	PP	-2.375 (0.391)		PP	-4.7990 (0.004)	
SRV	ADF	-1.4355 (0.930)	Non-Stationary	ADF	-5.769 (0.006)	Stationary
	PP	-1.609 (0.761)		PP	-4.199 (0.001)	
AGR	ADF	-6.402 (0.001)	Stationary	ADF	-3.560 (0.502)	Non-Stationary
	PP	-6.591 (0.000)		PP	-2.242 (0.451)	
MAN	ADF	-5.994 (0.002)	Stationary	ADF	-2.079 (0.99)	Non-Stationary
	PP	-5.360 (0.007)		PP	-2.360 (0902.)	
IND	ADF	-6915 (0.000)	Stationary	ADF	-1.962 (0.947)	Non-Stationary
	PP	-9.179 (0.000)		PP	-1.670 (0.740)	
UBP	ADF	-7.72 (0.001)	Stationary	ADF	-3.173 (0.107)	Non-Stationary
	PP	-6.993 (0.00)		PP	-3.972 (0.945)	

Source: Author's work based on E-Views 13 and data from the World Development Indicators (2023).

Cumulative sum (CUSUM) and cumulative sum square (CUSUMSQ)

Prior to the model estimation, the cumulative sum (CUSUM) and cumulative sum square (CUSUMSQ) were calculated to test the stability of the ARDL model. Figures 5 and 6 plots of the CUSUM and CUSUMSQ stability tests show that the ARDL regression line falls between the upper and lower bounds at the 5% significance level, implying that all coefficients in the error correction model are stable over time. Thus, the ARDL model is sufficient for a robust estimate of the short- and long-run nexus between energy consumption, economic growth, and diverse sources of CO2 emissions.

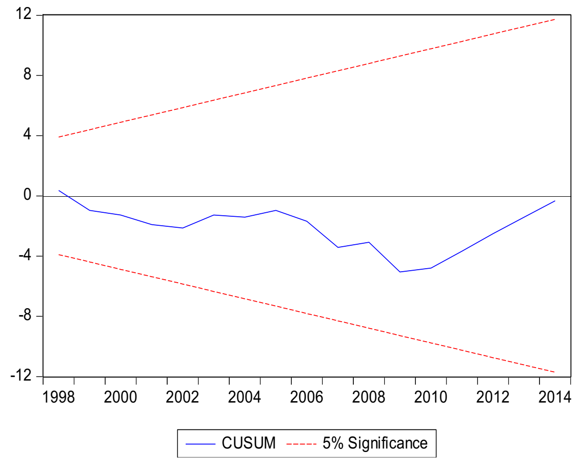

Figure 5 Cumulative sum (CUSUM)

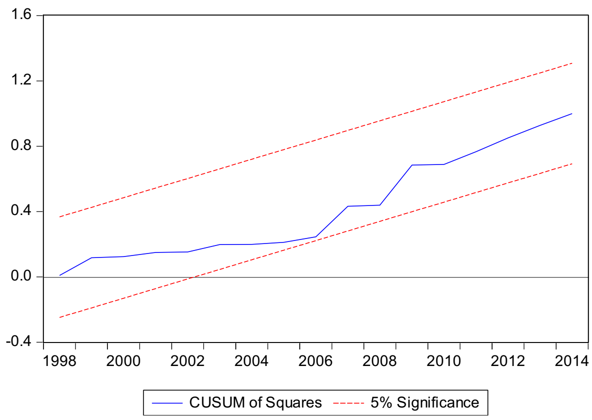

Figure 6 Cumulative sum square (CUSUMSQ)

Source: Author's work based on E-Views 13 and data from the World Development Indicators (2023).

4. ARDL Model Estimate

Table 4 Energy Consumption, Economic Growth and CO2 Emissions Long-Run Results

Panel A: Dependent Variable: D(LOGCO2)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
InENCO	0.766	0.104	7.352	0.0000
InPGDP	0.726	0.111	6.519	0.000
$InPGDP^2$	-0.280	0.070	-3.969	0.004
InNRR	0.005	0.101	0.052	0.958
InFDI	-0.087	0.036	-2.371	0.037
InAGR	0.424	0.065	6.450	0.000
InSRV	-0.031	0.065	-0.476	0.643
InMAN	0.007	0.010	0.683	0.508
InIND	-0.015	0.068	-0.228	0.823
InUBP	0.741	0.117	6.328	0.000
C	11.608	6.883	1.686	0.119
Panel B: Other Parameter Estimate				
F-Statistics	6.474	R^2	0.866	
D.Watson stat	2.151	CUSUM	Stable	
Prob	0.0000	CUSUM of Squares		
Panel C: F-Bounds Test				
Test Statistic	Value	Signif.	I(0)	I(1)
Asymptotic: n=1000				
F-statistic	5.6880	10%	1.8	2.8
K	9	5%	2.04	2.08 **
Panel D: Error Correction Model				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LOGCO2(-1))	-0.0125	0.0821	-0.1533	0.8809
CointEq(-1)*	-0.7669	0.0701	-10.929	0.0000

Source: Author's work based on E-Views 13 and data from the World Development Indicators (2023).

4.2 ARDL Long-Run Results

a. Energy Consumption, Economic Growth and CO2 Emissions

The findings reported in Panel A of Table 4 highlight the significant role of ENCO in stimulating economic growth across various sectors, which consequently diminishes environmental quality by increasing CO2 emissions. The elasticity coefficient of ENCO indicates that a 1% increase in energy consumption from fossil sources leads to a substantial 76% increase in CO2 emission. This result aligns with the general understanding that fossil fuel-based energy consumption is a major contributor to CO2 emissions. Udo et al. (2024), Samuel et al. (2021), Kwakwa et al. (2018), Halliru et al. (2020), Pata et al. (2021), Ridzuan et al. (2020), Zhan et al. (2021), and others have collaborated with the study findings, highlighting Nigeria's reliance on fossil energy to meet its energy demand and the resultant environmental implications.

Economic growth and CO2 emissions nexus: The EKC hypothesis states that a 1% increase in economic growth significantly increases CO2 emissions by 72%. The squared term of GDP per capita negatively impacted emissions, with a coefficient of 0.280. This confirms the presence of an inverted U-shaped nexus between economic growth and CO2 emissions, supporting the EKC hypothesis, which states that, in the initial phase of economic development, emissions increase with growth. However, beyond a certain threshold, the benefits of economic growth in terms of reducing carbon emissions begin to outweigh the initial increase in emissions. This study establishes an inverted U-shaped nexus, supporting the EKC hypothesis in the long run. Therefore, the turnaround point at which Nigeria's economic structure begins to shift and reduces emissions is 1.296. Beyond this turnaround point, further economic activities are characterized by a significant adoption of green technologies, stringent environmental regulatory frameworks, and a shift towards less polluting industries. Consequently, this leads to a decrease in carbon emissions, despite continued economic growth. The benefits of reaching this turnaround point are evidenced by the positive and significant impact of FDI and the growth of SRV, which reduce emissions by 0.087% and 0.031%, respectively. This indicates a shift towards green technologies due to investments in green energy sources and the influx of multinational firms from eco-friendly countries. However, urbanization and natural resource extraction have significantly increased CO2 emissions by 74% and 0.05%, respectively, exacerbating environmental concerns in Nigeria.

Panel B: The R2 value of 0.866 indicates the stability and reliability of the model. A Durbin-Watson statistic of 2.151 indicates the absence of first-order positive autocorrelation, enhancing the credibility of the study findings. Panel C: The bounds test results confirm the presence of a long-run nexus, with an F-statistic value of 5.688, which is greater than the upper and lower bound critical values at the 0.05% significance level. Panel D: Error correction (CointEq(-1) value of (-0.766) indicates the speed of convergence from short-run divergence caused by natural resource extraction, industrial activities, and population growth back to long-run equilibrium at a 76% annual convergence rate to improve environmental quality. These findings underscore the complex interplay among ENCO, PGDP, and CO2 emissions in Nigeria. The study findings emphasize the importance of transitioning to sustainable energy sources and implementing effective environmental policies to mitigate CO2 emissions and safeguard environmental quality.

Table 5 ARDL Energy Consumption, Economic Growth and Unbundled CO2 Emissions Indicators

Panel A: MEE		**(NOE)**		**(SFE)**	
Variable	**Coefficient**	**Coefficient**		**Coefficient**	
InENCO	0.952 (7.706)	0.303 (2.204)		0.924 (8.135)	
InPGDP	0.760 (6.110)	0.456 (8.905)		0.613 (6.124)	
$InPGDP^2$	-0.432 (-1.575)	-0.025 (-1.046)		-0.187 (-1.231)	
InNRR	0.0008 (0.214)	0.540 (7.877)		0.727 (7.076)	
InFDI	0.022 (0.572)	0.046 (1.389)		0.705 (6.681)	
InSRV	0.051 (0.837)	0.603 (7. 804)		0.410 (0.622)	
InAGR	0.553 (8.982)	0.601 (7. 889)		0.486 (0.760)	
InMAN	-0.0267 (-2.625)	-0.0089 (-1.687)		0.346 (2.836)	
InIND	0.057 (0.954)	0.062 (0.815)		0.532 (0.856)	
InUBP	0.7219 (6.245)	0.644 (5.354)		0.4860 (2.413)	
C	0. 813 (6.752)	0.720 (6.731)		0.757 (7.437)	
Panel B: Other Parameter Estimate					
R^2	0.716014	0.846		0.8362	
D.Watson stat	2.41	2.01		1.99	
CUSUM	Stable	Stable		Stable	
CUSUM of Squares					
Panel C: F-Bounds Test					
F-statistic	5.6597	4.957		4.1670	
K	10	K	10	K	10
I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
1.98	3.04**	1.98	3.04**	1.98	3.04**
Panel D: ECM					
Variable	Coefficient	Coefficient		Coefficient	

CointEq(-1)*	-0.660 (-7.821)	-0.6155 (-11.886)	-0.875 (-10.247)

Note: Inference is drawn at a 5% significance level

Source: Author's work based on E-Views 13 and data from the World Development Indicators (2023).

4.3 Energy Consumption and Unbundled CO2 Emissions Estimate

a. Methane (CH4)

The methane (CH4) emissions results, reported in Panel A of Table 5, revealed the impact of energy consumption on environmental quality through methane (CH4) emissions. Nigeria's economic growth was positively and significantly associated with methane emissions by 95%. This impact can be attributed to agricultural activities (especially livestock farming), landfills, natural gas systems, and coal mining, all of which contribute to economic growth. Methane (CH_4) emissions significantly reduce environmental quality, primarily because of their potent greenhouse gas (GHG) effects. Agricultural practices, particularly livestock farming, are significant sources of methane emissions. As such, a 1% increase in economic growth is associated with an increase in the demand for dairy products, natural gas, and coal mining, leading to higher methane emissions. The surge in economic growth of 76% reflects a corresponding increase in income level, leading to an increase in the purchasing power of economic agents to afford vehicles, which further exacerbates methane emissions. The squared term of economic growth, proxied by GDP per capita, negatively impacts emissions, with a coefficient of (-0.432). This confirms the presence of an inverted U-shaped nexus between economic growth and methane, aligned with the EKC hypothesis. The turnaround point where economic growth began to shift and methane emissions were reduced was 0.879. Factors such as the NRR, FDI, SRV, and IND did not significantly contribute to methane emissions. Urbanization significantly increases methane emissions by 72%, owing to heightened traffic congestion and increased vehicle usage in Nigeria's urban areas.

b. Nitrogen (NOx) (NOE)

Analysis of Nitrogen Oxide (NOx) emissions revealed an intertwined link between energy consumption, economic growth, industrialization, urbanization, natural resource extraction, and agricultural activities. A 1% change in NOx emissions was associated with a 49% increase in emissions in Nigeria. The non-significant coefficient of energy consumption on NOx emissions reveals the need for investment in green energy sources to enhance environmental quality in the long run. Economic growth positively impacts NOx with a negative squared term. Although the squared term is not significant, this suggests an inverted U-shaped nexus aligned with the EKC hypothesis. The turnaround point where economic growth began to shift and methane emissions were reduced was 9.12. The high turnaround point (GDP per capita level) indicates a dire need for significant economic growth before nitrous oxide emissions begin to decrease to improve environmental quality. This indicates the need for immediate interventions targeting agriculture and natural resource management to mitigate emissions in the short term. NRR (0.540), FDI (0.046), AGR (0.603), SRV (0.601), IND (0.062), and UBP (0.644) positively impacted NOx emissions, albeit with varying magnitudes, sizes, and significance levels. These findings align with those of Halliru et al. (2020), Pata et al. (2021), and Kwakwa et al. (2018), confirming the baseline level of NOx emissions when all independent variables are zero, indicating an increase due to natural sources and agricultural activities.

c. Solid sulfur (SO2) from Coal

The Solid Sulfur (SO2) emissions results show that a 1% increase in energy consumption through solid fuel emissions impacts environmental quality by 0.92%. Economic growth positively (0.612) impacts solid fuel emissions, with a negative squared term (-0.187), indicating a U-shaped nexus, thus aligning with the EKC hypothesis. The turnaround points where economic growth begins to shift and reduce SO2 emissions by approximately 1.64 indicates that as Nigeria's economy grows, solid fuel emissions will initially increase but eventually decrease as cleaner technologies are adopted. NRR (0.540), FDI (0.046), AGR (0.603), SRV (0.601), IND (0.062), and UBP (0.644) positively impacted NOx emissions, albeit with varying magnitudes, sizes, and significance levels. NRR (0.727), FDI (0.705), AGR (0.410), SRV (0.486), MAN (0.346), IND (0.532), and UBP (0.4860) positively impacted NOx emissions, albeit with varying magnitudes, sizes, and significance levels. These findings are consistent with those of the previous studies. The heavy reliance on solid fuel consumption for transportation, manufacturing, and agricultural activities significantly contributes to SO2 emissions. These findings align with those of Halliru et al. (2020), Pata et al. (2021), and Kwakwa et al. (2018), confirming the baseline level of SO2 emissions when all independent variables are zero, indicating a 75% increase in emissions in Nigeria. In Panel B, across the various sources of emissions, the model's stability and reality are reaffirmed by high R2 values and a D. Watson statistic of 2 or approximately 2 indicates the absence of first-order positive autocorrelation. In Panel C, the bounds test F-statistics value across the various emission sources is greater than the upper- and lower-bound critical values at a p-value of 0.05%. In Panel D, the error correction (CointEq(-1) value of (-0.660), (-0.615), and (-0.875) indicate a 66%, 61%, and 87% annual convergence rate towards reducing emissions through green energy practices.

Table 6 ARDL Energy Consumption and Unbundled CO2 Emissions Estimate (Continue)

Panel A: Gaseous Fuels Emission (GES)		Liquid Fuel Emissions (LFE)		Emissions RBCPS	
Variable	Coefficient	Coefficient		Coefficient	
InENCO	0.141 (9.468)	0.653 (9.623)		0.448 (8.233)	
InPGDP	0.714 (12.605)	0.702 (6.370)		0.663 (6.0835)	
$InPGDP^2$	-0.214 (-11.00)	-0.363 (-5.663)		-0.366 (-3.363)	
InNRR	0.113 (8.049)	0.205 (6.540)		0.029 (0.845)	
InFDI	-0.002 (-0.021)	-4.08E-05 (-0.00053)		0.0725 (1.342)	
InSRV	-0.113 (-0.671)	0.745 (3.549)		0.087 (1.612)	
InAGR	0.706 (9.590)	0.723 (3.535)		0.387 (7.109)	
InMAN	0. 812 (6.451)	0.040 (1.519)		0.0141 (1.947)	
InIND	-0.107 (-0.631)	0.725 (3.579)		0.076 (1.469)	
InUBP	0.094 (1.965)	0.264 (6.365)		0. 812 (7.283)	
C	0.144 (8.873)	0.731 (8.276)		0.9659 (0.167)	
Panel B: Other Parameter Estimate					
R^2	0.5922	0.868		0.935	
D.Watson stat	1.9159	2.02		2.454	
CUSUM	Stable	Stable		Stable	
CUSUM of Squares					
Panel C: F-Bounds Test					
F-statistic	6.512883	F-statistic	8.0419	F-statistic	6.822
K	10	K	10	K	10
I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
1.98	3.04**	1.98	3.04**	1.98	3.04**
Panel D: ECM					
Variable	Coefficient	Coefficient		Coefficient	
CointEq(-1)*	-0.9309 (-6.1745)	-0.7394 (-12.510)		-0.7191 (-6.7932)	

Note: Inference is drawn at a 5% significance level
Source: Author's work based on E-Views 13 and data from the World Development Indicators (2023).

d. Emissions from GES

From Table 6, Panel A, emissions stemming from GES exhibit a significant increase in response to economic growth through sectorial value addition. A 1% change in emissions, energy consumption, economic activity, natural resource rents, agricultural and manufacturing sector value addition, and urban population led to 70%, 14%, 71%, 11%, 70%, 81%, and 0.09%, respectively. Economic growth is positively and significantly associated with GES emissions (71%). This implies that as Nigeria's economy grows, emissions from gaseous fuels correspondingly increase. The squared term of economic growth is negative and significant, indicating an inverted U-shaped nexus aligned with the EKC hypothesis. This indicates that while economic growth initially increases GES emissions, at a turnaround point of 1.67, it reduces GES emissions. The relatively higher turnaround point indicates that substantial economic development is required before the environmental benefits from economic growth can be realized in terms of reducing gaseous fuel emissions.

e. Emissions from Liquid Fuel

The results for energy consumption through liquid fuel revealed a 65% positive and significant impact on economic growth. This indicates that the increased energy consumption depletes environmental quality by 65% through liquid fuel emissions. Economic growth was positively and significantly associated with 70 % %liquid fuel emissions. This implies that, as Nigeria's economy grows, emissions from liquid fuels increase. The negative and significant squared term of economic growth indicates an inverted U-shaped nexus aligned with the EKC hypothesis. This indicates that while economic growth initially increases liquid fuel emissions, after reaching a turnaround point of 0.97, liquid fuel emissions begin to decrease at a relatively earlier stage of economic growth compared to gaseous fuel emissions. This indicates that policies aimed at reducing liquid fuel emissions can be effective earlier in the economic development process. Other factors, such as NRR, FDI, and value addition from AGR, SR, IND, MAN, and UBP positively impact economic growth and environmental quality, albeit with varying magnitude, size, and significance levels. This study recommends the implementation of stringent fuel standards, promoting the use of alternative fuels, and investing in public transportation infrastructure to help reduce liquid fuel emissions as the economy grows.

f. Emissions from RBCPS

Emissions from residential buildings and commercial and public services (RBCPS) have increased in response to economic growth through energy consumption. A 1% increase in energy consumption correspondently depletes environmental quality by 44%. Economic growth is positively and significantly associated with emissions. This implies that, as Nigeria's economy grows, emissions from residential and commercial services increase by 70%. The negative and significant squared term of economic growth indicates an inverted U-shaped nexus aligned with the EKC

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hypothesis. This indicates that while economic growth initially increases emissions, after reaching a turnaround point of 0.91, emissions from residential buildings and commercial services start to decrease at a relatively earlier stage of economic growth compared to gaseous fuel emissions and are similar to liquid fuel emissions. This implies that actionable energy and environmental policies focusing on energy-efficient building codes, retrofitting existing buildings, and promoting the use of renewable energy sources in residential and commercial sectors will lead to relatively early emission reductions in the economic growth trajectory. Other factors such as NRR and FDI, along with value addition from AGR, SR, IND, MAN, and UBP, positively impact economic growth and environmental quality through the various sources of emissions, albeit with varying magnitudes, sizes, and significance levels. The results in Panel B across all sources of emissions demonstrate model stability and reliability with high R2 values and a Watson statistic of 2 or approximately 2, ruling out possible first-order positive autocorrelation. The bounds test results in Panel C across all emission sources confirm the existence of a long-run nexus between energy consumption, economic growth, and CO2 emissions, supported by an F-statistic value exceeding critical values at a significance level of 0.05%. Panel D indicates across all sources of emissions, the convergence of short-run divergence towards long-run equilibrium, with a significant CointEq(-1) value of (-0.930; -0.730;-0.719), revealing a 93%, 73%, and 72% annual convergence rate towards reducing emissions through green energy practices. These comprehensive findings shed light on the intricate energy consumption, economic growth, and various sources of emissions in Nigeria, emphasizing the urgency of transitioning towards sustainable energy practices to mitigate environmental degradation and ensure long-term ecological sustainability. The turnaround points from the EKC analysis suggest that, with early and effective policy interventions, Nigeria can reduce certain emissions early in its economic development, emphasizing the need for environmental regulations and green technology investments from the onset. Sector-specific strategies are crucial, as gaseous fuel emissions require long-term approaches, whereas liquid fuel and residential/commercial emissions can be mitigated more quickly with targeted policies. Achieving sustainable development involves balancing economic growth with environmental protection guided by the EKC framework. Substantial investments in green technologies, renewable energy, and energy efficiency are essential for meeting and surpassing these turnaround points. Additionally, raising public awareness and education about sustainable practices and environmental protection is vital to garner support for emission-reducing policies.

5. Conclusions

Energy availability and accessibility are crucial for Nigeria's economic industrialization and sustainability across various consumption sectors. Nigeria's heavy reliance on fossil energy to bridge the 80% energy demand-supply gap underscores its status as one of the most carbon-intensive economies, making it highly susceptible to adverse climate change effects. This study confirms the EKC hypothesis with sector-specific impacts, necessitating targeted policies for different sectors. Methane emissions from transportation, NOx emissions from agriculture and industry, and solid fuel emissions from coal significantly contribute to GHG emissions. To achieve environmental sustainability and overall development, governments must incentivize investment in green energy sources such as solar, wind, and hydropower; implement stringent emissions standards; and promote eco-friendly urbanization initiatives, such as public transportation infrastructure to reduce reliance on personal vehicles. Nigeria accounted for approximately 11,605.207 units of registered motor vehicles in 2021, with Southwest Nigeria accounting for 27%, South-South 20.1%, North Central 19.3%, North-West 11.8%, and North-East 3.2% as a share of households with registered motor vehicles by zone. Leveraging environmentally conscious FDI inflows is necessary to reduce CO2 emissions through international partnerships and technology transfers. An inclusive approach integrating regulatory measures, green technology investments, sustainable practices, and public awareness is essential for addressing Nigeria's energy consumption-CO2 emissions nexus, aligned with SDGs 7, 8, 13, and 17.

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