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An Analysis of Energy Transition and Environmental Sustainability in Nigeria

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Abstract— *The increasing use of fossil fuel for economic activities in developing countries and the quest to cleaner environment in line with the sustainable development goals make it imperative to examine how energy transition affect the environment in Nigeria. In order to achieve the purpose of the study energy used such as: solar energy consumption, hydropower energy consumption and natural gas consumption were used as proxies of energy transition while environmental sustainability was measured by carbon dioxide (CO_2) emissions per capita. Data on the above variables were sourced from the Nigerian Electricity Regulatory Commission (NERC), National Bureau of Statistics (NBS) and World Development Indicators (WDI) of the World Bank. The Autoregressive Distributive Lag (ARDL) approach was used after preliminary test of descriptive statistics and unit root. The results of the ARDL estimation indicated that solar energy consumption and natural gas consumption have negative and significant effect on CO_2 emission per capita in both long-run and short-run, hydropower energy consumption has a beneficial and considerable impact on per capita CO2 emissions in both the long and short term, whereas hydropower energy has a negative one. as well as a negligible impact on per capita carbon dioxide emissions, both in the near and far future. Sequel to the findings, the study concluded that energy transition plays a significant vital role in promoting environmental sustainability in Nigeria. The study recommended among others that Nigeria should aggressively expand investment in solar power generation and adoption at both utility and household levels. This can be achieved by: Providing fiscal incentives for solar panel manufacturers and distributors, expanding rural electrification programs as well as enhancing grid integration of solar energy.*

Keywords— *Energy Transition, Environmental sustainability, CO_2 emission per capita, Solar Energy Consumption, Hydropower Energy Consumption, Natural Gas Consumption.*

I. Introduction

The global debate on climate change and environmental degradation has placed increasing emphasis on the role of energy systems in achieving a sustainable future. Energy is central to economic growth, industrialization, and social development; however, the reliance on fossil fuels has created a pattern of unsustainable growth marked by rising greenhouse gas emissions, air pollution, and depletion of natural ecosystems. In response to these challenges, the concept of energy transition has emerged as a viable pathway toward sustainability (Geels, Sovacool, Schwanen & Sorrell, 2017). Energy transition refers to the shift from fossil fuel–based energy sources such as coal and oil to cleaner, renewable, and low-carbon alternatives such as natural gas, solar, wind, hydro, geothermal, and bioenergy. This transformation is not only essential for combating climate change but also holds immense potential for improving the overall quality of the environment. Therefore, the positive effects of energy transition on environmental sustainability are increasingly evident as countries adopt renewable energy policies and technologies that align with global development goals (Owusu & Asumadu-Sarkodie, 2016). One of the most profound impacts of energy transition is the reduction of greenhouse gas emissions and the subsequent mitigation of climate change. Fossil fuel combustion is the largest contributor to carbon dioxide emissions, which trap heat in the atmosphere and lead to global warming. By replacing fossil-based energy with renewable sources, energy transition offers an effective mechanism to decouple economic growth from environmental harm. This not only helps stabilize global temperatures but also safeguards vulnerable ecosystems from the adverse impacts of climate change such as desertification, loss of biodiversity, and extreme weather events. The positive implications for sustainability are therefore tied to the long-term preservation of the planet's natural balance (Ekechukwu & Eziefula, 2025). The energy transition promotes better air quality and healthier ecosystems in addition to reducing climate change. Conventional fossil fuel use produces harmful pollutants like sulfur dioxide, nitrogen oxides, and particulate matter, which degrade air quality and damage both human health and the natural environment. Renewable energy systems, by contrast, generate power with little to no emissions of these pollutants, thereby reducing respiratory diseases in humans and protecting wildlife from harmful atmospheric conditions. The result is a cleaner, safer, and more sustainable environment where ecosystems can thrive and populations can enjoy improved well-being. This shift illustrates how energy transition promotes the dual goals of environmental protection and public health enhancement (Obada, 2024).

However, despite possessing significant solar, wind, and hydro resources, Nigeria's energy mix remains dominated by gas-fired power plants (accounting for approximately 80% of grid electricity) and pervasive petrol and diesel generators, which citizens and businesses rely on due to an unreliable grid. This reliance is exacerbated by a rapidly growing population, increasing energy poverty, and gas flaring. The World Bank reported that in 2022, gas flaring in Nigeria released 20 million tons of CO_2 equivalent, highlighting a dual failure: the wasteful emission of greenhouse gases from the oil sector and the simultaneous inability to harness this gas for domestic power needs, thereby undermining both environmental and energy access goals (World Bank, 2023). Consequently, Nigeria's transition is severely lagging, with renewable energy (excluding large hydro) contributing less than 2% to the

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electricity mix by 2022, far short of policy ambitions like the Energy Transition Plan (ETP) which targets net-zero by 2060. This slow progress is compounded by severe environmental degradation. The Food and Agriculture Organization (FAO) recorded a continued decline in forest cover, with a deforestation rate of approximately 3.7% per year between 2015 and 2020, one of the highest globally. This loss of carbon sinks, coupled with emissions from generators, estimated to cost the economy nearly $22 billion annually in fuel and maintenance (International Monetary Fund, 2023) as well as and gas flaring, places Nigeria's sustainable development goals in peril. The problem, therefore, is a critical policy and implementation gap where fossil fuel dependency continues to drive environmental unsustainability, while the transition to cleaner energy systems remains impeded by infrastructural deficits, regulatory uncertainties, and inadequate investment. It is with the identified problem, this study aimed at examining the effect of energy transition on environmental sustainability in Nigeria. Specifically, the study examined the effect of solar energy consumption, hydropower energy consumption as well as natural gas consumption on CO_2 emission per capita in Nigeria.

II. Literature Review

Theoretical Framework

i. Energy Transition Theory

The Energy Transition Theory was developed in the 1980s by scholars studying long-term shifts in energy use, most prominently Smil (1987), who provided a systematic framework for understanding historical and structural changes in energy systems. The theory builds on earlier works on technological change and economic transitions, explaining how societies gradually move from reliance on one dominant energy source (e.g., wood, coal, or oil) to another, often cleaner and more efficient source (such as natural gas, nuclear, or renewables). Smil (2010) emphasized that energy transitions are not merely technical shifts but socio-economic transformations that influence industrial processes, consumption patterns, and environmental outcomes. Later, Grübler (1998) expanded the theory, highlighting that energy transitions unfold over decades, often shaped by policy, market incentives, and societal demand for cleaner energy. At its core, the Energy Transition Theory posits that energy systems evolve in stages, with each transition associated with major technological and institutional innovations. According to Smil (2010), the transition from biomass to coal in the 18th and 19th centuries enabled the Industrial Revolution, while the 20th-century shift to oil and natural gas transformed transportation and global trade. Fouquet and Pearson (2012) added that these transitions are driven not only by resource depletion but also by the need for greater efficiency, cost reduction, and environmental sustainability. The theory therefore explains both historical shifts and contemporary debates around moving from fossil fuels to renewable energy in the 21st century. Importantly, it underscores that transitions are path-dependent, gradual, and influenced by geopolitical, economic, and technological factors.

Applied to environmental sustainability, the Energy Transition Theory provides a framework for understanding how moving from fossil fuels to renewables reduces environmental degradation. In the short run, reliance on coal and oil contributes significantly to greenhouse gas emissions, air pollution, and ecosystem destruction. However, as the theory suggests, the gradual adoption of renewable energy sources such as solar, wind, and hydropower enables decoupling of economic growth from carbon emissions. Hence, renewable-based transitions foster sustainability by reducing carbon footprints and supporting global climate goals. Thus, the Energy Transition Theory explains that Nigeria and other developing economies can achieve environmental sustainability by accelerating the transition through renewable energy adoption, stricter policies, and innovation incentives. This implies that the energy transition is not only an economic necessity but also an ecological imperative for long-term survival.

ii. Environmental Kuznets Curve (EKC) Hypothesis

The Environmental Kuznets Curve (EKC) was first developed by economist Simon Kuznets (1955) in the context of income inequality and economic growth, and later adapted in the early 1990s by Grossman and Krueger (1991) to explain the relationship between environmental quality and economic development. The Environmental Kuznets Curve (EKC) hypothesis suggests that as an economy grows, environmental degradation initially increases due to industrialization, urbanization, and overreliance on non-renewable resources, but after reaching a certain income threshold, environmental quality begins to improve as societies demand cleaner technologies and enforce stricter environmental policies. According to Grossman and Krueger (1995), environmental indicators such as air pollution and water contamination initially worsen with economic expansion but tend to improve once countries become wealthier and prioritize sustainability. Similarly, Panayotou (1993) argued that the Environmental Kuznets Curve (EKC) demonstrates how economic growth can serve as both a cause and a solution to environmental degradation, provided the right institutional and policy frameworks are in place.

When applied to the energy transition, the Environmental Kuznets Curve (EKC) provides useful insights into how shifting from fossil fuels to renewable energy sources affects environmental sustainability. In the early stages of energy transition, developing countries like Nigeria may still rely significantly on coal and crude oil, resulting in higher greenhouse gas emissions and degradation of ecosystems. However, as income levels and technological capacity grow, these countries are expected to adopt renewable energy sources such as solar, wind, and hydropower, thereby reducing pollution and achieving sustainable growth. Hence, renewable energy adoption plays a critical role in bending the Environmental Kuznets Curve (EKC) downward earlier by decoupling economic growth from carbon emissions.

Empirical Review

Alwell, Oladosu and Leonard (2025) examined the effect of renewable energy on economic growth in Nigeria from 1990 to

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2022. The techniques of data analysis adopted include: descriptive statistical technique, ADF unit root test, bounds cointegration test and Autoregressive Distributed Lag (ARDL) approach. The findings of the study showed that hydro energy has a positive and significant effect on Real Gross Domestic Product in Nigeria in both short run and long run while that solar energy also has a positive and significant effect on Real Gross Domestic Product in Nigeria in both short run and long run.

Johnson, Hamisu, Umar and Mwakapwa (2025) estimated an optimal energy mix for Nigeria's transition, applying threshold analysis to relate renewable output shares to emissions outcomes. The key finding is that below a certain renewable share, gains can be muted or offset by fossil back-up; beyond the threshold, emissions fall more sharply as system integration improves.

Ekechukwu and Eziefula (2025) aimed to analyze the alternative energy sources in Nigeria, their potentials, alternative energy policy implementation and its challenges. Qualitative research approach was utilized as this study's research methods while SALSA framework (search, appraisal, synthesis and analysis) was utilized to search, evaluate and analyze the selected literatures for this study's analysis. This analysis underscored that Nigeria has solar, wind and biomass as the major alternative energy resources, while solar alternative energy has potential of about 5250Wh/m2 with an average solar radiation of 19.8 MJ/m2 /day over 6 hours.

Ajia (2025) examined renewable energy policy and sustainable development in Nigeria using a systematic scoping review from 2000 to 2025. The study showed that Nigeria's ability to attain sustainable development is directly and indirectly influenced by renewable energy legislation. It has the potential to act as a moderating force in the interaction between sustainable development and renewable energy systems, especially in terms of supply and demand. Renewable energy is a direct contributor to Nigeria's sustainable development in terms of its direct effects.

Obada (2024) provided a comprehensive review of renewable energy resources and transition pathways in Nigeria. The study synthesized evidence on solar, wind, hydro, and biomass potentials, identifies barriers (grid constraints, intermittency, finance), and maps policy instruments for decarbonization. The study found that Nigeria's technical renewable energy potential is large enough to materially lower emissions if supported by stable policies, infrastructure upgrades, and domestic manufacturing capacity.

Yusuf (2023) examined how Nigeria's socioeconomic variables mediate ecological sustainability, focusing on the environmental payoff from shifting the energy mix. Using modern time-series techniques on Nigerian data, the study modeled links among energy use, growth, and ecological indicators. The study found that greater renewable penetration and efficiency policies are associated with lower environmental pressure, while fossil-heavy consumption raises it. The study concluded that an energy transition centered on clean generation is pivotal to improving Nigeria's environmental quality.

In his summary of the prospects and obstacles to the development of clean and sustainable technologies in Nigeria, Yekini (2024) provided a review. A perceptive literature review identified the main challenges impacting the seamless installation of renewable energy across the nation and offered pertinent solutions. rising renewable energy investment in the nation.

George, Anthony, Eberechukwu, Ezeh, Okenyeka and Mbadiwe (2023) examined impact of renewable energy consumption on economic growth in Nigeria from 1990 to 2020. The study used Toda-Yamamoto augmented granger causality test to test for the nature of the relationship between the two variables and Auto Regressive Distributed Lag (ARDL) bounds test to examine the impact of renewable energy consumption on economic growth. The study found a bi-directional relationship between the variables. The regression results also demonstrated a substantial beneficial influence of renewable energy use on economic expansion.

Fasheyitan, Omankhanlen and Okpalaoka (2022) analyzed the effects of renewable energy consumption and financial development in Nigeria, asking whether deeper finance helps scale renewables and cut emissions. Using econometric models with Nigerian annual data, the study reports that renewable energy consumption significantly reduces CO_2 emissions, and that financial development supports this effect by easing capital constraints for clean energy investment.

Oluwatoyin, Huseyin and Mehdi (2022) examined the impact of renewable energy consumption (RNEW) on economic growth (RGDP) in Nigeria within the period of 1990Q1-2019Q4 using a non-linear autoregressive distributed lag (NARDL) model. According to the NARDL data, a positive RNEW shock lowers RGDP, while a negative shock raises RGDP over the long term. A positive shock of RNEW has a small impact on RGDP, increasing it, whilst a negative shock has a minor impact on RGDP, lowering it. Because of the nature and source of renewable energy utilized in Nigeria, primarily wood biomass, a positive shock in RNEW harms RGDP.

From 1971 to 2014, Ozoegwu and Akpan (2021) conducted research on the course of solar energy policy in Nigeria in order to promote a safer and cleaner development. Through a directional distance function approach, the study estimated both the energy efficiency and the environmental energy efficiency scores in the sample. The results showed that ignoring the undesirable output, i.e. dioxide carbon emissions is associated with environmental degradation, overestimates countries' energy inefficiency.

III. METHODOLOGY

The analytical framework of this study hinged on Energy Transition Theory because of its relevance to this study as it justifies how moving from fossil fuels to renewables reduces environmental degradation. Furthermore, the model of the study is built on the model of Alwell, Oladosu and Leonard (2025) with slight modification. The modified model is functionally stated as:

$$CPC = f(SEC, HEC, NGC) \quad (1)$$

Equation (1) is explicitly stated as:

$$CPC_t = \beta_0 + \beta_1 SEC_t + \beta_2 HEC_t + \beta_3 NGC_t + \mu_t \quad (2)$$

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Equation (2) is transformed into a log linear form as follows:
$\text{InCPC}_t = \beta_0 + \beta_1\text{InSEC}_t + \beta_2\text{InHEC}_t + \beta_3\text{InNGC}_t + \mu_t$ (3)
A Priori Expectation (Economic Theory): $\beta_1 < 0$, $\beta_2 < 0$, $\beta_3 < 0$.
Where: CPC = CO_2 emissions per capita, SEC = Solar energy consumption, HEC = Hydropower energy consumption, NGC = Natural gas consumption, β_0 = Constant variable in the model, β_1 = Parameter of solar energy consumption, β_2 = Parameter of hydropower energy consumption, β_3 = Parameter of natural gas consumption, $_t$ = Time subscript, In = natural log, μ_t = Error term.
The Autoregressive Distributed Lag (ARDL) model specification of the above model is given as;

$$\ln(CPC_t) = \delta_0 + \beta_{1i}\ln(CPC_{t-1}) + \beta_{2i}\ln(SEC_{t-1}) + \beta_{3i}\ln(HEC_{t-1}) + \beta_{4i}\ln(NGC_{t-1}) + \sum_{t=1}^{p}\alpha_{1i}\Delta 1n(CPC_{t-1}) + \sum_{t=1}^{q}\alpha_{2i}\Delta 1n(SEC_{t-1}) + \sum_{t=1}^{q}\alpha_{3i}\Delta 1n(HEC_{t-1}) + \sum_{t=1}^{P}\alpha_{4i}\Delta 1n(NGC_{t-1}) + \varepsilon_{1i} \quad (4)$$

Δ = Difference operator and indicates the optimum lag; t = Time lag; δ_0 = Constant variable; $\beta_1 - \beta_4$ = long-run dynamic coefficients of the model; $\alpha_1 - \alpha_4$ = Short-run dynamic coefficients of the model; ε_{1i} = Serially uncorrelated stochastic term with zero mean and constant variance.
In furtherance, the short run dynamic parameters are arrived at by the estimation of an error correction model linked with the long-run estimates. The model is stated below:

$$\Delta\ln(CPC_t) = \delta_0 + \sum_{t=1}^{p}\alpha_{1i}\Delta 1n(CPC_{t-1}) + \sum_{t=1}^{q}\alpha_{2i}\Delta 1n(SEC_{t-1}) + \sum_{t=1}^{q}\alpha_{3i}\Delta 1n(HEC_{t-1}) + \sum_{t=1}^{q}\alpha_{4i}\Delta 1n(NGC_{t-1}) + \delta ECMT_{t-1} + \varepsilon_{1i} \quad (5)$$

Data Analysis Technique

The Autoregressive Distributed Lag (ARDL) technique was adopted in this study. ARDL technique is an econometric approach used to analyze both short-run dynamics and long-run relationships among variables in time series analysis, particularly when the variables are a mix of stationary at level [I(0)] and stationary at first difference [I(1)]. It is especially useful in small sample studies, as it produces unbiased long-run estimates and valid inferences even with limited data. The ARDL model is adopted when preliminary unit root tests show that variables are integrated of different orders (I(0) and I(1)), making traditional cointegration techniques like Johansen unsuitable. Its importance lies in its ability to capture both immediate (short-run) adjustments and equilibrium (long-run) relationships, incorporate lag structures that account for dynamic interactions, and provide a robust framework for policy analysis and forecasting in applied economic research.

IV. RESULTS AND DISCUSSION

Descriptive Analysis

Descriptive statistics of this study are summarized in Table 1:

TABLE 1: Descriptive Statistics

	CPC	SEC	HEC	NGC
Mean	0.687441	81.19265	6338.824	194080.7
Median	0.654000	2.250000	5995.000	141580.3
Maximum	0.911000	816.0000	8349.000	455258.3
Minimum	0.501000	0.020000	4387.000	45025.50
Std. Dev.	0.110620	191.3077	1066.157	131464.9
Skewness	0.305996	2.683237	0.452437	0.596928
Kurtosis	1.845875	9.346562	2.290589	1.892766
Jarque-Bera	2.417599	97.86033	1.872922	3.755950
Probability	0.298556	0.000000	0.392013	0.152899
Sum	23.37300	2760.550	215520.0	6598744.
Sum Sq. Dev.	0.403814	1207754.	37510773	5.70E+11
Observations	**34**	**34**	**34**	**34**

Source: *Authors' Computation, 2025.*

The results in Table 1 showed that CO_2 emission per capita (CPC) has a mean of 0.69 metric tons with relatively low variability (Std. Dev. = 0.11), indicating that per-person emissions have remained fairly stable over the study period. Its skewness (0.30) and kurtosis (1.84) suggest a distribution that is slightly right-skewed and flatter than normal, while the Jarque-Bera probability (0.29) confirms that the series is normally distributed. Solar energy consumption (SEC), on the other hand, shows a mean of 81.19 GWh but a median of only 2.25, highlighting that growth was heavily concentrated in later years. The very high standard deviation (191.30), skewness (2.68), and kurtosis (9.34) confirm that the distribution is highly skewed with extreme outliers, a reflection of Nigeria's late but rapid expansion in solar adoption. The Jarque-Bera test (p = 0.000) indicates that solar energy consumption (SEC) data deviate significantly from normality, which is consistent with the uneven nature of solar energy deployment. For hydropower energy consumption (HEC), the mean is 6,338.82 GWh with a median of 5,995, showing relative stability compared to solar. The standard deviation (1,066.15) indicates moderate fluctuations, while skewness (0.45) and kurtosis (2.29) suggest the distribution is near-normal, supported by the Jarque-Bera probability of 0.39. Natural gas consumption (NGC) records the highest mean at 194,080.7 MMSCF, with a wide range between the minimum (45,025.5) and maximum (455,258.3), reflecting Nigeria's heavy reliance on gas over the years. Its standard deviation (131,464.9) shows large variability, though skewness (0.59) and kurtosis (1.89) point to a slightly right-skewed and relatively flat distribution. The Jarque-Bera test (p = 0.15) suggests approximate normality.

Trend Analysis

The trends and pattern of all the research variables were confirmed with graphs as shown in Figure 1:

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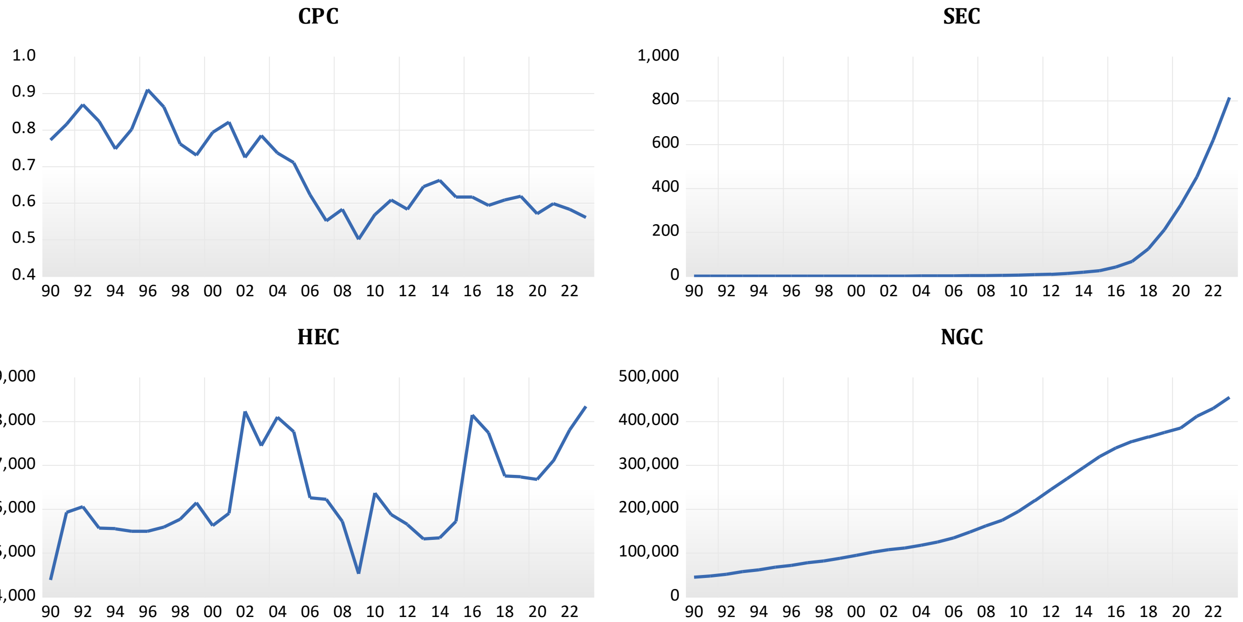

Figure 1: Line Graph Showing the Trend in the Research Variables

Figure 1 illustrate distinct trends in Nigeria's energy use and carbon emissions between 1990 and 2023. CO_2 emissions per capita (CPC) show a general decline from around 0.9 tons in the early 1990s to below 0.6 tons in recent years, suggesting some relative decoupling of emissions from population growth. Solar energy consumption (SEC) remained negligible until the mid-2000s but experienced exponential growth after 2015, highlighting Nigeria's late but accelerating adoption of solar as part of its energy transition. Hydropower consumption (HEC) fluctuates considerably over the years, reflecting variability in water availability, infrastructure reliability, and investment cycles, though it shows recovery toward the end of the period. Meanwhile, natural gas consumption (NGC) demonstrates a steady upward trend, rising from below 100,000 MMSCF in 1990 to over 400,000 MMSCF by 2023, reinforcing its role as the backbone of Nigeria's energy system. Overall, the plots reveal a gradual diversification of energy sources, with gas dominance, volatile hydropower, and rapidly emerging solar, alongside relatively stable but low per-capita carbon emissions.

Multicollinearity Test

For the purpose of this study, correlation matrix was used to detect the presence or absence of multicollinearity problem. The result of the correlation matrix is presented in Table 2:

The correlation matrix in Table 2 shows that multicollinearity is not a serious concern among the variables. Carbon dioxide emissions per capita (CPC) have weak negative correlations with solar energy consumption (SEC, –0.47), hydropower consumption (HEC, –0.21), and natural gas consumption (NGC, –0.11), suggesting that increases in renewable and gas use are generally associated with lower per-capita emissions, though the relationships are not very strong. Since none of these correlation coefficients approach the conventional threshold of 0.8 or higher, which would indicate harmful multicollinearity, the variables can be included together in regression analysis without major risk of distorted coefficient estimates due to linear dependence. This implies the model is structurally sound for examining the effects of different energy sources on emissions.

TABLE 2: Correlation Matrix

	$InCPC_t$	$InSEC_t$	$InHEC_t$	$InNGC_t$
$InCPC_t$	1			
$lnSEC_t$	-0.46875	1		
$lnHEC_t$	-0.20674	0.511715	1	
$lnNGC_t$	-0.10916	0.381269	0.445077	1

Source: *Authors' Computation, 2025.*

Unit Root Test

It has become a necessity in econometric modelling to determine the order of integration of series in order to avoid a situation of spurious results. As a result, Augmented Dickey Fuller (ADF) was used in this study to check for unit root. The aim of conducting this test is to avoid spurious regression which comes from regressing one non-stationary variable upon another non-stationary variable. The results of the Augmented Dickey-Fuller test are presented in Table 3 below:

TABLE 3: Augmented Dickey-Fuller (ADF) Unit Root Test Results

	Augmented Dickey-Fuller (ADF)					
Variables	**Levels**	**5% Critical Value**	**1st Difference**	**5% Critical Value**	**I(d)**	**Stationary @**
$lnCPC_t$	-1.291648	-2.954021	-6.286114***	-2.957110	I(1)	1st Difference
$lnSEC_t$	-0.052034	-2.967767	-5.980101	-2.960411	I(1)	1st Difference
$lnHEC_t$	-3.011429	-2.954021	-	-2.998064	I(0)	Level
$lnNGC_t$	-1.129166	-2.957110	-7.914062	-2.957110	I(1)	1st Difference

Note: *, **, and *** denote significance at 10%, 5% and 1%, respectively
Source: *Authors' Computation, 2025.*

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The Augmented Dickey-Fuller (ADF) test results in Table 3 indicate that the variables exhibit mixed orders of integration. CO_2 emissions per capita (CPC), solar energy consumption (SEC), and natural gas consumption (NGC) are all non-stationary at their levels since their test statistics are less in absolute values than the 5% critical values. However, each becomes stationary after first differencing, with highly significant test statistics, showing they are integrated of order one, I(1). In contrast, hydropower energy consumption (HEC) is stationary at level, with its ADF statistic that is greater than the 5% critical value, implying it is integrated of order zero, I(0). This combination of I(0) and I(1) variables suggests the data are suitable for cointegration analysis, such as the Autoregressive Distributed Lag (ARDL) approach, which can handle a mix of stationary and first-difference stationary variables without the need for pre-testing for uniform integration order. This supports the robustness of further econometric modeling to examine long-run and short-run dynamics among emissions and energy consumption sources.

Bounds Cointegration Test

Since the variables of this study have mixed stationarity, that is, integrated of order zero [I(0)] and integrated of order one [I(1)], we therefore proceed to establish or ascertain the existence or nonexistence of long-run cointegrating relationship among the variables in the equation using bounds cointegration test. This test was carried out using Autoregressive Distributed Lag (ARDL) bounds approach. The result of ARDL bounds cointegration test is presented in Table 4:

The bounds cointegration test results in Table 4 show clear evidence of a long-run relationship among the variables. At the 5% significance level, the computed F-statistic (5.55) is higher than both the lower bound (2.79) and the upper bound (3.67). This leads to the rejection of the null hypothesis of no long-run relationship, confirming that CO_2 emissions per capita (CPC) are cointegrated with solar energy consumption (SEC), hydropower consumption (HEC), and natural gas consumption (NGC). In practical terms, this implies that despite short-run fluctuations, there exists a stable long-run equilibrium connection between emissions and energy consumption sources in Nigeria. This finding justifies the use of the ARDL bounds testing approach and supports further investigation into both the short-run dynamics and long-run coefficients to understand how renewable and non-renewable energy consumption jointly shape environmental sustainability outcomes.

TABLE 4: Bounds Cointegration Test Results

Significant Level	Critical Value Bound		Hypothesis	F-Statistics
	I(0) Bound	I(1) Bound		
10%	2.37	3.2	**H0:** There is no long run relationship	5.550467***
5%	2.79	3.67		
2.5%	3.15	4.08		
1%	3.65	4.66		
F_{CPC}(CPC/SEC, HEC, NGC)			K = 3	

Note: K = Number of regressors; *, ** and *** denote significance at 10%, 5% and 1% level, respectively.
Source: *Authors' Computation, 2025.*

Autoregressive Distributive Lag (ARDL) Long-Run and Short-Run Dynamics

The long run and short run dynamic effects of energy transition on environmental sustainability was estimated using ARDL method. The results are presented in Table 5:

TABLE 5: ARDL Long-Run and Short-Run Estimation Results

Dependent Variable = $lnCPC$
Selected Model: ARDL(1, 1, 1, 4)

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
ARDL Long-Run Results				
$lnSEC_t$	-0.375083	0.137192	-2.734008	0.0107
$lnHEC_t$	-1.078979	0.604850	-1.783880	0.0889
$lnNGC_t$	-0.208045	0.093751	-2.219128	0.0358
C	9.443548	6.382277	1.479652	0.1538
EC = LOG(CPC) - (-0.3751*LOG(SEC) -1.0790*LOG(HEC) -0.2080*LOG(NGC) + 9.4435)				
ARDL Short-Run Results				
D($lnSEC_t$)	-2.794904	0.782759	-3.570582	0.0018
D($lnHEC_t$)	-0.696786	0.691909	-1.007048	0.3254
D($lnNGC_t$)	-0.375660	0.113243	-3.317294	0.0028
D($lnNGC_{t-1}$)	-0.459174	0.781638	-0.587451	0.5632
D($lnNGC_{t-2}$)	0.160233	0.819684	0.195481	0.8469
D($lnNGC_{t-3}$)	0.045616	0.094532	0.482545	0.6336
CointEq(-1)*	-0.390010	0.100097	-3.896325	0.0008

Adjusted R^2 = 0.527054
Durbin-Watson stat = 2.341556

Source: *Authors' Computation, 2025.*

The long-run ARDL estimates show that all three energy sources contribute to reducing CO_2 emissions per capita (CPC), though their strengths differ. Solar energy consumption (SEC) has a negative and statistically significant coefficient (–0.375, p = 0.0107), indicating that a 1% increase in solar use reduces emissions by about 0.38%. This aligns with the role of solar as a clean and renewable source of energy, suggesting that its gradual expansion in Nigeria is beneficial for sustainability.

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Hydropower consumption (HEC) also has a negative coefficient (–1.079), implying a stronger emissions-reducing effect, but its weak significance at the 10% level reflects the challenges of reliability in Nigeria's hydropower sector. Natural gas consumption (NGC) is also significant (–0.208, p = 0.0358), with a smaller impact compared to solar and hydropower, but it still underscores natural gas as a relatively cleaner alternative to oil and coal in Nigeria's energy mix.

In the short run, solar energy again shows the strongest impact on reducing emissions, with a large negative and significant coefficient (–2.795, p = 0.0018). This suggests that increases in solar energy adoption yield immediate and substantial environmental benefits. Hydropower's short-run coefficient (–0.697) is negative but statistically insignificant, meaning its contribution to emissions reduction is less consistent in the immediate term, possibly due to variability in water resources and infrastructural bottlenecks. For natural gas, the short-run contemporaneous coefficient is negative and significant (–0.376, p = 0.0028), showing that increased gas consumption reduces emissions immediately. However, the lagged values of natural gas are insignificant, indicating that the effect is not sustained over multiple periods but rather occurs contemporaneously.

The error correction term (–0.39, p < 0.05) confirms the presence of a stable long-run equilibrium relationship among CO_2 emissions per capita (CPC), solar energy consumption (SEC), hydropower consumption (HEC), and natural gas consumption (NGC), with about 39% of any short-run disequilibrium corrected annually. The adjusted R^2 of 0.53 shows that just over half of the variation in emissions is explained by the energy transition variables, while the Durbin-Watson statistic (2.34) indicates no serious autocorrelation. Taken together, these results suggest that solar energy provides both immediate and long-term emissions reductions, hydropower has potential but is less consistent in the short run, and natural gas serves as an important transitional fuel that helps lower emissions in the short run while contributing moderately to long-run sustainability.

Post-Estimation Tests

The results of the post-estimation tests are presented in Table 6:

TABLE 6: Post-Estimation Test Results

Test	Test Type	Null Hypothesis (H_0)	X^2 Value	X^2 Prob	Decision
Normality Test	Jarque-Bera Test	Normal distribution exists	0.36333	0.83387	Do not Reject H_0
Serial Correlation Test	Breusch-Godfrey LM Test	Serial correlation does not exist	0.666843	0.5249	Do not Reject H_0
Heteroscedasticity Test	Breusch-Pagan-Godfrey	Homoscedasticity exists	1.060740	0.4256	Do not Reject H_0
Functional Form Test	Ramsey RESET	Model is stable	1.236886	0.2793	Do not Reject H_0

Source: *Authors' Computation, 2025.*

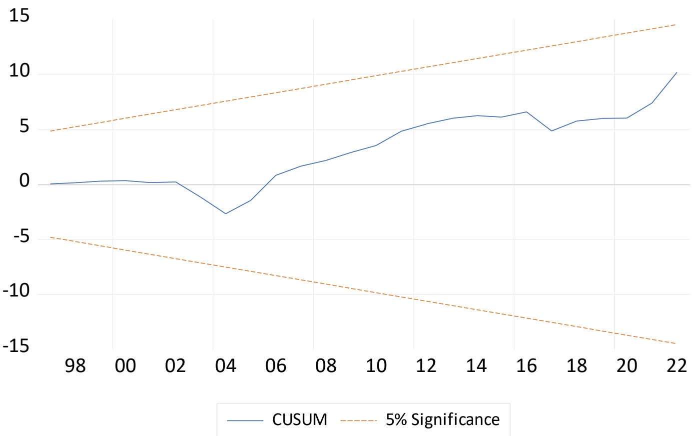

Figure 2: Stability Cusum Test

The post-estimation test results in Table 6 indicate that the ARDL model satisfies the key diagnostic requirements for reliability and validity. The Jarque-Bera normality test yields a probability value of 0.83387, which is much greater than the 5% significance level, indicating that the residuals are normally distributed and thus, Because of non-normal errors, the model is unbiased. Likewise, the Breusch-Godfrey LM test for serial correlation produces a probability value of 0.5249, indicating the absence of autocorrelation in the residuals, which increases the the estimated coefficients' consistency and efficiency. Furthermore, the Breusch-Pagan-Godfrey test for heteroscedasticity returns a probability of 0.4256, indicating that the residuals have constant variance and the model is free from heteroscedastic distortions. Lastly, the Ramsey RESET test records a probability of 0.2793, meaning the functional form of the model is correctly specified without omitted variable bias or misspecification. Taken together, these diagnostic checks confirm that the ARDL estimates are statistically robust, valid, and reliable for inference and policy recommendations.

The cumulative sum (CUSUM) indicates that the CUSUM line stayed within the 5 percent critical bound while neither did CUSUM plot crosses the 5 percent critical lines. The implication of this is that there is stability of the long-run coefficients of the study variables.

Discussion of Findings

This study has empirically analyzed the annual time series data sourced in determining the effect of energy transition on environmental sustainability in Nigeria from 1990 to 2023 using Autoregressive Distributive Lag (ARDL) estimation technique. First, the finding that emanated from this study revealed that solar energy consumption has a negative and significant effect on CO_2 emissions per capita in both short-run and long-run. In addition, in both the short term and the long term, hydropower energy usage has a little and detrimental influence on per capita CO2 emissions. Lastly, the results of this study showed that natural gas consumption has a negative and significant effect on CO_2 emissions per capita in both short run and long run. This finding conforms to the finding of Fasheyitan, Omankhanlen and Okpalaoka (2022) who established that that renewable energy consumption significantly reduces CO_2 emissions in Nigeria. Also, Yusuf (2023) found that an energy transition centered on clean generation is pivotal to improving Nigeria's environmental quality. Finally, Ozoegwu and Akpan (2021) discovered that dioxide carbon emissions linked to environmental degradation overestimate the energy inefficiency of nations.

V. Conclusion and Recommendations

Drawing from the foregoing, this study has examined the effect of energy transition on environmental sustainability in Nigeria. The findings of the study indicated that solar energy consumption and hydropower energy consumption are important indicators of energy transition that have negative effects on CO_2 emissions per capita in Nigeria. Premised on the findings, the study concluded that energy transition plays a significant vital role in promoting environmental sustainability in Nigeria. Based on these findings, the following policy recommendations are proffered:

i. Nigeria should aggressively expand investment in solar power generation and adoption at both utility and household levels. This can be achieved by: Providing fiscal incentives for solar panel manufacturers and distributors, expanding rural electrification programs as well as enhancing grid integration of solar energy.
ii. Government should expand and modernize its hydropower plants while integrating climate-resilient water resource management strategies. This should involve: Rehabilitating existing hydropower stations, developing small and medium-scale hydropower projects in rural communities and introducing adaptive water management policies.
iii. Government should prioritize natural gas as a transitional energy source to displace high-carbon fuels like coal, diesel, and fuel oil. This can be implemented by expanding gas-to-power infrastructure and encouraging independent power producers (IPPs) to utilize natural gas as well as scaling up domestic gas utilization policies.

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