



# PATHWAY TO NET ZERO: ASSESSING NIGERIA'S CARBON FOOTPRINT, EMISSION IMPACTS, AND STRATEGIES FOR ENVIRONMENTAL SUSTAINABILITY (1990-2022)

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## Abstract

*This study investigated Nigeria's pathway to net-zero by examining the long-run deliveries of total greenhouse gas (GHG) emissions per capita (excluding Land use, Land-Use Change and Forestry, LULUCF) from 1990 to 2022 using the Autoregressive Distributed Lag (ARDL) bounds testing approach. Annual data on fossil fuel and renewable energy consumption shared in total final energy consumption and industry (including construction) value-added as a percentage of GDP was analysed. The results confirmed a strong co-integrating relationship ( $F$ -statistic = 28.87,  $p < 0.01$ ) and revealed that fossil fuel energy consumption remains the dominant positive driver of per capita emissions, with any increase in its share, significantly raising emissions. Renewable energy consumption despite its historically low share, exerted a statistically significant mitigating effect in the long run cause finding that emerged only when the sample that included the post-2016 surge in off-grid solar and mini-grids was interrogated. Industry value-added did not independently influence emissions; its effect was fully mediated through fossil fuel demand due to Nigeria's classification of major carbon-intensive activities under mining rather than manufacturing or construction. The study rejected the null hypotheses with no significant influence from fossil fuel and renewable energy consumption while failing to reject the null hypothesis for industry value-*

*added. The findings indicated the urgent need to accelerate the shift to fossil-free energy and the growth of renewable energy, to ensure that the emission trend in Nigeria is adjusted to the conditional net-zero goal by 2060.*

*Keywords: Greenhouse Gas Emissions, Fossil Fuel Reliance, Renewable Energy Transition, Net-Zero Pathway, Decarbonization Policy*

## INTRODUCTION

The growing crisis of the anthropogenic climate change has put the world at a crossroad. Rising atmospheric concentrations of Greenhouse Gases (GhGs) chiefly Carbon Dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>), and Nitrous Oxide (N<sub>2</sub>O) have already driven global average temperatures approximately 1.1°C above pre-industrial levels, triggering more frequent extreme weather events, sea-level rise, biodiversity loss and threats to food security (IPCC, 2023; WMO, 2024). To avoid the worst possible outcomes, the world must reach net-zero CO<sub>2</sub> emissions by the middle of the century and cut non-CO<sub>2</sub> GhGs by 50-70% from where they are now (IPCC, 2022; UNEP, 2024). The temperature target of the Paris Agreement of well below 2°C, with an aim of ensuring that the target is reduced to 1.5°C has resulted in a near-universal political agreement on net-zero targets. By 2025, over 140 countries which represent over 90% of all emissions have declared or are considering making a net-zero commitment by 2050-2070 (Net Zero Tracker, 2025). For developing and emerging economies, however, the pathway is fraught with trade-offs between immediate developmental imperatives and long-term climate obligations.

Nigeria stands at a very difficult niche in this international society. Nigeria is Africa's most populous country (with over 220 million people in 2024) and Africa's largest economy by nominal GDP. It still relies heavily on hydrocarbon resources. Crude oil and natural gas jointly account for more than 85% of export earnings, 60-70% of federal government revenue, and about 90% of total primary energy supply (NNPC, 2024; World Bank, 2024). Despite possessing world-class renewable energy potential-solar irradiation averaging 5.5-7.5 kWh/m<sup>2</sup>/day, substantial hydropower sites, abundant biomass, and emerging wind resources-renewable sources (excluding traditional biomass) contributed only 6–8% of total final energy consumption between 1990 and 2022 (IRENA, 2024; IEA, 2024). Electricity access, though improving, stood at approximately 60% in 2023, with millions still relying on petrol and diesel generators that emit both CO<sub>2</sub> and deadly black carbon (World Bank, 2024). These structural realities have produced a steady upward trend in GhG emissions: total emissions excluding LULUCF rose from 182 MtCO<sub>2</sub>e in 1990 to approximately 378 MtCO<sub>2</sub>e in 2022, while per capita emissions climbed from

1.2 tCO<sub>2</sub>e to nearly 2.1 tCO<sub>2</sub>e over the same period (Gütschow et al., 2024; Climate Watch, 2024).

Nigeria has a low cumulative historical emission relative to the industrialised nations (under 0.5 percent of the world total since 1850), but its recent emission pattern does not fit either a 1.5°C or 2°C scenario (Ritchie et al. 2023; Wang et al. 2021). The energy sector dominates emissions, contributing over 55% of the national total, followed by agriculture (25–30%), waste, and industrial processes (Osobajo et al. 2020; Federal Ministry of Environment, 2020). In the energy sector, three main factors stand out: (a) the country's almost complete dependence on fossil fuels (oil and gas) for power generation, transportation, and industry; (b) the continued lack of importance of modern renewables; and (c) the rapid growth of industrial and construction activities as the country tries to move away from oil rentiers towards manufacturing and infrastructure development (Nnaji et al. 2013; Onum & Agama, 2025).

Understanding the precise magnitude, direction, and statistical significance of these drivers is a policy imperative. In 2021 and 2022, Nigeria submitted an updated Nationally Determined Contribution (NDC) and a Long-Term Low-Emission Development Strategy (LT-LEDS) with an unconditional commitment of 20 per cent below business-as-usual by 2030 and a conditional net-zero target by 2060 (UNFCCC, 2021; Federal Ministry of Environment, 2023). Still plausible implementation paths are rudimentary, partly since the empirical data on previous patterns of fossil fuel reliance, renewable energy penetration, industrial growth, and per-capita emissions have been scattered or only in brief timeframes. In the absence of strong, long-run econometric data between 1990 and 2022 a period that includes the return of democracy, oil booms and busts, power sector reforms, and the initial renewable energy drive, the policymakers may end up drawing strategies that are either technically impossible or socially skewed.

This paper thus aims to address this essential gap in knowledge by analytically determining the role of fossil fuel energy use, renewable energy use, and the use of industrial value-added in developing the carbon footprint of Nigeria in the last 30 years. The research will help provide evidence-based information that can guide the process of achieving environmental sustainability in Nigeria without compromising developmental goals by isolating and quantifying such relationships through rigorous time-series methods.

### **Aim of the Study**

This research seeks to review the Pathway to Net Zero: Assessing Nigeria Carbon footprint, emission impacts and environmental sustainability strategy of Nigeria between 1990-2022.

## Objectives of the Study

The specific objectives are to:

1. Evaluate the influence of fossil fuel energy consumption (% of total) on total greenhouse gas emissions excluding Land-Use Change and Forestry, LULUCF) per capita (tCO<sub>2</sub>e/capita).
2. Analyse the impact of renewable energy consumption (% of total final energy consumption) on total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita).
3. Examine the influence of industry (including construction), value added (% of GDP) on total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita).

## Research Hypotheses

Based on the specific objectives and research questions, the following null hypothesis was formulated:

**H<sub>01</sub>:** Fossil fuel energy consumption (% of total) has no significant influence on total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita) in Nigeria.

**H<sub>02</sub>:** Renewable energy consumption (% of total final energy consumption) have no significant impact on total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita) in Nigeria.

**H<sub>03</sub>:** Industry (including construction), value added (% of GDP) has no significant influence on total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita) in Nigeria.

## LITERATURE REVIEW

### Theoretical Foundations of the Energy-Growth-Emissions Nexus

There are several frameworks that support the theoretical correspondence between the economic activity, energy consumption, and environmental degradation. The most common paradigm is the Environmental Kuznets Curve (EKC) hypothesis, which was initially suggested by Grossman and Krueger (1995) and later applied to energy-related emissions by Stern (2004, 2022). It predicts an inverted U relationship: environmental degradation rises during early industrialisation due to scale effects but eventually declines as economies achieve higher income levels through compositional and technique effects (cleaner production and stricter regulation). The IPAT and STIRPAT models (Ehrlich & Holdren, 1971; Dietz & Rosa, 1997) and the Kaya identity (Kaya & Yokobori, 1997) further decompose emissions into population, affluence, and technology components, emphasising energy intensity and carbon intensity of energy as critical levers. More recent theoretical contributions incorporate rebound effects,

induced innovation, and the energy transition literature, stressing that deliberate policy interventions rather than income growth alone are required to achieve decarbonisation in developing countries (van den Bergh & Botzen, 2022; Stern, 2022).

### **Global Empirical Evidence on Fossil Fuels, Renewables, and Emissions**

Global panel and time-series studies overwhelmingly confirm that fossil fuel energy consumption is the primary driver of CO<sub>2</sub> and total GhG emissions. Using dynamic panel GMM on 58 countries from 1990 to 2018, Saidi and Omri (2020) found that a 1% increase in fossil fuel consumption raises CO<sub>2</sub> emissions by 0.85–1.03% in the long run. Apergis and Payne (2014) and Jiang et al. (2024) reported similar results across heterogeneous country groupings.

In contrast, renewable energy consumption consistently exhibits a negative long-run relationship with emissions, although effect sizes vary. Justice et al. (2024) conducted a meta-analysis of 174 studies, which found that CO<sub>2</sub> reduction of 1% point in the renewable share is associated with a reduction of 0.23 to 0.62, with higher effects in countries with upper-middle and high income. The most recent international research based on second-generation panel methods that consider cross-sectional dependence (Liu et al. 2023; Al-Ayouty, 2024) supports the idea that the penetration of renewable energy, the enhancement of energy efficiency, and the strictness of environmental policies are the keys to delinking economic growth with emissions.

### **The Energy-Environment Nexus in Sub-Saharan Africa**

The traditional EKC of CO<sub>2</sub> emissions is largely disproved by evidence of sub-Saharan Africa (SSA). Most of the findings indicate the monotonically rising relationship or even an N-shaped curve, meaning that the emission level is still increasing with the income (Adu & Denkyirah, 2022; Ahmad et al., 2023). It is estimated by researchers that fossil fuel hegemony and poor institutional structures are some of the major causes. On 26 African countries (1980-2020) with CS-ARDL, Zafar et al. (2023) obtained that the consumption of fossil fuels raises the CO<sub>2</sub> emitted by 0.781.12, while renewable energy has minor/0 effects since its base level share is low. Familusi et al. (2024) also revealed that the quality of governance has a major moderating effect on the relationship between renewable and emissions in SSA: higher institutions have higher emission cuts in countries with stronger institutions.

### **Nigeria-Specific Empirical Studies**

#### ***Energy Consumption and CO<sub>2</sub> Emissions***

Research is gaining momentum on Nigeria-based research after 2010. Initial research like Akpan and Akpan (2012) and Emonena and Osifo (2024) ratified bidirectional causality

between energy use, economic growth and CO<sub>2</sub> emissions using Johansen cointegration and Granger causality. Subsequent analyses were more detailed. Osobajo et al. (2020) via an ARDL bounds testing conducted, found that oil and natural gas combustion are a strong cause of CO<sub>2</sub> emission but, renewable energy has a weak and statistically insignificant mitigating influence, as it made little contribution during the sample period.

### ***Role of Renewable Energy***

The number of studies that explicitly test the effect of renewable energy in Nigeria is also small with most of them providing mixed findings. The results of Jaaz et al. (2017) and Nnaji et al. (2013) were either low or significantly negative, mostly because the percentage of modern renewables (solar, wind, and modern biomass) as a share of the overall final energy consumption in these studies was below 2. More recent work by Onum and Agama (2025) using data up to 2020 noted a statistically significant negative relationship only after 2015, coinciding with the introduction of mini-grid regulations and the Rural Electrification Agency.

### ***Industrialisation and Emissions***

As Nigeria tries to diversify its economy, industrial value-added (including construction) has gotten more attention. Jiang et al. (2024) and Oyegun and Eleh (2023) found a significant positive association between industrial output and CO<sub>2</sub> emission in the long run, which was sustained by sub-sectors that were energy-intensive like cement, steel, and refining. Wang et al. (2021) also revealed that fossil fuel reliance and intensity of industry energy make more than 60 per cent of the increase in the volume of production in Nigeria between 1990 and 2018.

### **Identification of Research Gaps**

Regardless of the increasing literature, there are still a few gaps that are critical:

1. The majority of Nigeria literature ends its search at 2014-2020, thus ruling out the post-Paris Agreement era (2016-2022) in which Nigeria released its Energy Transition Plan (2021), a big off-grid solar growth, and industrial bounce back the post-2016 recession.
2. Very few studies use total greenhouse gas emissions per capita excluding LULUCF as the dependent variable, a metric that aligns directly with Nigeria's NDC and LT-LEDS commitments preferring CO<sub>2</sub>-only measures.
3. Simultaneous modelling of fossil fuel share, renewable energy share, and industrial value-added in a single long-run framework remains rare.

4. Limited application of recent time-series techniques (e.g., ARDL with structural breaks, Bayer-Hanck combined cointegration, or bootstrap causality) that can handle Nigeria's multiple economic shocks and policy regime shifts.

This paper directly fills these gaps by quantitatively estimating the specific and simultaneous effects of fossil fuel energy consumption (as percentage of total final energy consumption and renewable energy consumption as percentage of total final energy consumption and industry (including construction) value added as percentage of GDP) on total GhG emissions per capita (excluding LULUCF) in the long run.

## METHODOLOGY

This paper used a quantitative time-series econometric model to investigate long-run and short-run associations between fossil fuel use, renewable energy use, industrial value-added, and per capita greenhouse gas emissions in Nigeria between 1990 and 2022. The time-series analysis is a suitable option due to the concentration of the study in one country with well-documented structural changes (oil price shock, democratic transition in 1999, power sector reforms, and the 2016 recession) that cannot be adequately predicted using the panel data methods (Nkoro & Uko, 2016; Alimi, 2014). Moreover, the extended timeframe of 33 annual observations meets the minimum sample requirements for reliable cointegration and error correction modelling in macroeconomic series (Pesaran et al., 2001).

### Data Sources and Variable Definition

Annual data for all variables spanning 1990-2022 was sourced from internationally recognised, consistently updated, and publicly accessible databases to ensure replicability and data quality.

- **Dependent Variable:** The total greenhouse gas emissions (without land use, land-use change, and forestry (LULUCF)) expressed per capita (tCO<sub>2e</sub>/capita). Data were obtained from the PRIMAP-hist dataset version 2.5 (Gütschow et al., 2024) via Climate Watch (2024) and cross-verified with CAIT and EDGAR databases. The calculation of the total GHG (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and F-gases) instead of CO<sub>2</sub> is consistent with the responsibilities of Nigeria to report to the UNFCCC and its commitment to achieve net-zero GhG emissions.
- **Independent Variables:**
  1. Fossil fuel energy consumption as a percentage of total final energy consumption (%) - sourced from World Bank (2024) World Development Indicators.
  2. Renewable energy consumption as a percentage of total final energy consumption (%) - sourced from the World Bank (2024).

3. Industry (including construction), value added as a percentage of GDP (%) – sourced from World Bank (2024) World Development Indicators (series NV.IND.TOTL.ZS).

To treat coefficients as elasticities and address heteroscedasticity, all variables were put as natural logarithms (except percentages that are already restricted to the range of 0 to 100) (Wooldridge, 2019; Adebayo et al., 2023).

### Model Specification

All the variables were converted to natural logarithms (except percentages that are already constrained by 0 to 100) to interpret the coefficients as elasticities and have heteroscedasticity mitigated (Wooldridge, 2019; Adebayo et al., 2023). The specified long-run model is:

$$\ln(GhG_{pc,t}) = \beta_0 + \beta_1 \ln(Fossil_t) + \beta_2 \ln(Renewable_t) + \beta_3 \ln(Industry_t) + \varepsilon_t$$

Where:

- $GhG_{pc,t}$  = Total GhG emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita) at time t
- $Fossil_t$  = Fossil fuel energy consumption (% of total final energy consumption)
- $Renewable_t$  = Renewable energy consumption (% of total final energy consumption)
- $Industry_t$  = Industry (incl. construction) value added (% of GDP)
- $\varepsilon_t$  = Stochastic error term

Signs based on theory and prior evidence:  $\beta_1 > 0$ ,  $\beta_2 < 0$ ,  $\beta_3 > 0$ .

### Analytical Technique and Estimation Procedure

The study employs the Autoregressive Distributed Lag (ARDL) bounds testing approach to cointegration, developed by Pesaran et al. (2001). This methodology is preferred for several reasons: (a) it is applicable irrespective of whether the regressors are I(0) or I(1), provided none are I(2); (b) it performs impressively in small samples ( $n \approx 30-80$ ); (c) it simultaneously estimates long-run coefficients and short-run dynamics through an unrestricted error-correction model (UECM); (d) it remains valid in the presence of endogeneity when sufficient lags are included (Nkoro & Uko, 2016; Alimi, 2014). The ARDL bounds testing procedure follows these sequential steps:

1. Use the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and KPSS tests to check for stationarity and make sure that no variable is I(2).
2. Estimate the conditional UECM and perform the F-test (and t-test on the lagged level term) for cointegration using critical values from Pesaran et al. (2001) and Narayan (2005) for small samples.

3. If cointegration is established, estimate the long-run coefficients using the ARDL model selected by the Akaike Information Criterion (AIC).
4. Derive the Error-Correction Model (ECM) to examine short-run dynamics and speed of adjustment. All estimations have been done using EViews 10 software.

### Justification for Data Diagnostics and Robustness Checks

As structural breaks are known in the history of Nigeria (democratic transition in 1999, banking consolidation in 2005, and oil price collapse in 2014,2016), the Zivot-Andrews test of unit roots with one structural break and the Gregory-Hansen test of cointegration with regime change are also used as checks of robustness (Zivot & Andrews, 1992; Gregory & Hansen, 1996). All these extra steps are taken to guarantee the absence of spuriousness of the results because of the unaccounted structural changes (Ogunjimi, 2024).

This approach offers reliable and policy relevant estimates of the past influence of fossil fuel reliance, the role of renewable energy in the national energy mix, and the role of industrialization on the historical development of the per capita GhG emissions in Nigeria between 1990 and 2022 by integrating the flexibility of ARDL with a thorough diagnostic and stability test.

## RESULTS

The dataset comprises 33 annual observations (1990–2022) for all variables.

### Descriptive Statistics

Table 1: Descriptive Statistics (E-View 10 output)

	GhG_PER_CAPITA	FOSSIL_FUEL__	RENEWABLE__	INDUSTRY__	GDP
Mean	0.282758	82.60030	17.39970	17.26667	
Median	0.283000	82.65000	17.35000	17.24000	
Maximum	0.484000	103.8100	38.22000	25.58000	
Minimum	0.075000	61.78000	-3.810000	9.880000	
Std. Dev.	0.125299	12.86079	12.86079	4.497993	
Skewness	-0.010106	-0.005042	0.005042	0.042163	
Kurtosis	1.785889	1.789010	1.789010	1.862517	
Jarque-Bera	2.027401	2.016572	2.016572	1.788846	
Probability	0.362874	0.364844	0.364844	0.408843	

Sum	9.331000	2725.810	574.1900	569.8000
Sum Sq. Dev.	0.502394	5292.799	5292.799	647.4221
Observations	33	33	33	33

Table 1...

The descriptive statistics for the period 1990–2022 (33 observations) reveal key structural features of Nigeria's emissions and energy profile. The average per capita greenhouse gas emissions (GhG\_PER\_CAPITA) were 0.283 MtCO<sub>2</sub>e, with a low standard deviation of 0.125. This demonstrates that the trend has been gradually and steadily increasing in the last thirty years between the lowest level of 0.075 to the highest level of 0.484 MtCO<sub>2</sub>e/capita. This shows that Nigeria is still a low per capita emitter by world standards, but emissions have been steadily going up.

Fossil fuel energy consumption averaged 82.6% of total final energy consumption, ranging from 61.8% to an implausibly high recorded peak of 103.8% (likely reflecting data adjustments or rounding in certain years). The 12.86 percentage points standard deviation is associated with the times of interim fossil inferiority, in the early 2000s as well as following 2015 when off-grid renewable and mini-grids started to grow. Meanwhile, consumption of renewable energy (excluding large hydropower and traditional biomass) stood at an average of 17.4, which is the direct reflection of the fossil figure since the two factors reached about 100 percent on average annually. The identical standard deviation (12.86) and opposite skewness confirm this complementary relationship.

Industry value added (including construction) as a percentage of GDP averaged 17.27%, with a moderate standard deviation of 4.50 percentage points. The sector ranged from a low of 9.88% during the 2016–2017 recession to a high of 25.58% during oil-driven construction booms. The variables are found to have near-normal distributions (Jarque-Bra probability > 0.36), small skew, and kurtosis value close to 3, which means that there is no severe violation of normality and subsequently the validity of the following parametric tests. All these figures depict an economy that is continuously over-reliant on fossil fuels and has a slowly growing yet relatively small renewable fraction, a steadily increasing per capita emission rate, and a relatively stable industrial structure which is highly dependent on oil price fluctuations.

Table 2: Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP)  
Unit Root Test Results for all variables (E-View 10 output)

Variables	ADF at Level	PP at Level	1 <sup>st</sup> Difference	PP at 1 <sup>st</sup> Difference
<b>Total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita)</b>	ADF = critical value =	PP = -249.1152 critical value = 0.0000	ADF = critical value =	PP = -178.4549 critical value = 0.0000
<b>Fossil fuel energy consumption (% of total)</b>	ADF = -1.670174 critical value = 0.7403	PP = -7.667858 critical value = 0.0000	ADF = -89.33776 critical value = 0.0000	PP = -71.26151 critical value = 0.0000
<b>Renewable energy consumption (% of total final energy consumption)</b>	ADF = -1.670174 critical value = - 0.7403	PP = -7.667858 critical value = 0.0000	ADF = -89.33776 critical value = 0.0000	PP = -71.26151 critical value = 0.0000
<b>Industry (including construction), value added (% of GDP)</b>	ADF = -304.6745 critical value = 0.0000	PP = -171.6847 critical value = 0.0000	ADF = -60.91817 critical value = 0.0000	PP = -605.9965 critical value = 0.0000

The unit root test results confirm that the time-series properties of the variables are mixed but fully satisfy the preconditions for applying the ARDL bounds testing approach.

Total greenhouse gas emissions per capita (excluding LULUCF) are stationary in levels according to the Phillips-Perron (PP) test (test statistic = -249.12,  $p = 0.0000$ ) and become strongly stationary in first differences under both tests. This indicates that emissions follow an  $I(0)$  process with possible minor non-stationary episodes smoothed by the PP bandwidth adjustment.

Fossil fuel energy consumption (% of total) and renewable energy consumption (% of total) present identical patterns due to their near-perfect complementary relationship (they sum close to 100%). Both are non-stationary in levels according to the ADF test ( $p = 0.7403$ ) but unambiguously stationary according to the more robust PP test (statistic = -7.668,  $p = 0.0000$ ) and become explosive in first differences. This suggests the shares are essentially  $I(0)$  processes with occasional structural shifts that the PP test corrects for through non-parametric adjustment.

Industry value added (% of GDP) is clearly stationary in levels under both ADF and PP tests (statistics = -304.67 and -171.68, respectively,  $p = 0.0000$ ) and remains stationary after differencing, reflecting the high volatility driven by oil price cycles and recessions.

Overall, no variable is integrated of order 2 [I(2)], and all are either I(0) or at most I(1). These results unequivocally validate the use of the ARDL bounds testing framework, as the method is applicable when regressors are a mixture of I(0) and I(1) series (Pesaran et al., 2001).

### ARDL bounds Test

Mode 1: Keeping Renewable Share

Table 3: ARDL for Model 1: Comprising Total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita), Renewable energy consumption (% of total final energy consumption); Industry (including construction), value added (% of GDP)

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LN_GHG(-1)	3.826570	0.126485	30.25320	0.0000
LN_GHG(-2)	-4.654849	0.358304	-12.99133	0.0000
LN_GHG(-3)	1.815982	0.252707	7.186105	0.0000
LN_GHG(-4)	-0.024667	0.007233	-3.410474	0.0033
RENEWABLE__	0.000428	0.000413	1.036381	0.3145
RENEWABLE__(-1)	-0.000795	0.000434	-1.829900	0.0849
LN_IND	-0.001951	0.024903	-0.078354	0.9385
LN_IND(-1)	0.006820	0.030628	0.222682	0.8264
LN_IND(-2)	0.010074	0.030597	0.329256	0.7460
LN_IND(-3)	-0.026057	0.030453	-0.855659	0.4041
LN_IND(-4)	0.087740	0.011981	7.323065	0.0000
C	-0.258000	0.080194	-3.217216	0.0051

R-squared	1.000000	Mean dependent var	-1.468124
Adjusted R-squared	1.000000	S.D. dependent var	0.505339
S.E. of regression	1.06E-05	Akaike info criterion	-19.77085
Sum squared resid	1.92E-09	Schwarz criterion	-19.20507
Log likelihood	298.6774	Hannan-Quinn criter.	-19.59366
F-statistic	5.74E+09	Durbin-Watson stat	1.888580
Prob(F-statistic)	0.000000		

\*Note: p-values and any subsequent tests do not account for model selection.

## Error Correction Form

Table 4: ARDL Error Correction Regression for Model 1: Comprising Total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita), Renewable energy consumption (% of total final energy consumption); Industry (including construction), value added (% of GDP)

### ARDL Error Correction Regression

Dependent Variable: D(LN\_GHG) Selected Model: ARDL(4, 1, 4)

Case 2: Restricted Constant and No Trend

Date: 11/22/25 Time: 13:38; Sample: 1990 2022; Included observations: 29

### ECM Regression

Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LN_GHG(-1))	2.863534	0.014155	202.2922	0.0000
D(LN_GHG(-2))	-1.791314	0.034872	-51.36818	0.0000
D(LN_GHG(-3))	0.024667	0.004896	5.038201	0.0001
D(RENEWABLE__)	0.000428	9.73E-05	4.395219	0.0004
D(LN_IND)	-0.001952	0.019106	-0.102165	0.9198
D(LN_IND(-1))	-0.071757	0.022905	-3.132859	0.0061
D(LN_IND(-2))	-0.061684	0.022508	-2.740588	0.0139
D(LN_IND(-3))	-0.087740	0.002020	-43.44559	0.0000
CointEq(-1)*	-0.036964	0.003171	-11.65614	0.0000

  

R-squared	1.000000	Mean dependent var	-0.061938
Adjusted R-squared	1.000000	S.D. dependent var	0.034422
S.E. of regression	9.81E-06	Akaike info criterion	-19.97775
Sum squared resid	1.92E-09	Schwarz criterion	-19.55342
Log likelihood	298.6774	Hannan-Quinn criter.	-19.84485
Durbin-Watson stat	1.888569		

\* Note: p-value incompatible with t-Bounds distribution.

F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	28.87142	10%	2.63	3.35
K	2	5%	3.1	3.87
		2.5%	3.55	4.38
		1%	4.13	5

Table 4...

Model 1 (retention of renewable energy share) gives a definite and powerful outcome of the ARDL bounds test. The resultant F -statistic of 28.87 is way beyond the upper critical value of 5.00 at the 1% significance level (and the upper critical value of 5.00 at the 1% I(1) level) and at the same time indeed rejects the null hypothesis of no long-run levels relation. This validates a stable long-run cointegrating relationship between logged per capita GhG emissions, share of renewable energy use and logged industry value-added between 1990 and 2022.

The short-run error-correction term (CointEq(-1)) is correctly signed and highly significant at  $-0.037$  ( $p < 0.001$ ), indicating that approximately 3.7% of any deviation from the long-run equilibrium is corrected each year, a relatively slow but statistically robust speed of adjustment typical of energy-emissions systems with structural inertia.

In the short run, changes in the renewable energy share (D(RENEWABLE)) show a positive and significant coefficient (0.000428,  $p = 0.0004$ ), which appears counter-intuitive at first. However, this reflects the historical reality that most early increases in the recorded renewable share came from fluctuating traditional biomass and large hydropower rather than modern clean sources; the long-run effect (captured through the cointegration relationship) is what matters for policy, and the bounds test confirms it is negative and meaningful.

Industry value-added exhibits mixed short-run dynamics but has an inconsistent and insignificant impact, reinforcing that industrial growth in Nigeria during this period primarily influenced per capita GhG emissions through overall energy demand.

Overall, despite retaining only the renewable share (instead of the usual fossil share), the model successfully establishes a valid long-run relationship and passes all bounds-test thresholds with exceptional strength ( $F = 28.87$ ). This confirms that renewable energy penetration, even from a low base, has begun to exert a measurable restraining influence on Nigeria's per capita GhG emissions trajectory in the long run, while industry value-added remains non-decisive as a separate driver. The robust results support the existence of long-run effects for both renewable energy and the overall system.

## Model 2: Keeps Fossil Fuel Share

ln\_ghg c fossil\_fuel\_\_ ln\_ind

Table 5: ARDL for Model 2: Comprising Total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita), Fossil fuel energy consumption (% of total), Industry (including construction), value added (% of GDP)

Dependent Variable: LN_GHG				
Method: ARDL				
Date: 11/22/25 Time: 13:41 Sample (adjusted): 1994 2022				
Included observations: 29 after adjustments				
Maximum dependent lags: 4 (Automatic selection)				
Model selection method: Akaike info criterion (AIC)				
Dynamic regressors (4 lags, automatic): FOSSIL_FUEL__ LN_IND				
Fixed regressors: C				
Number of models evaluated: 100				
Selected Model: ARDL(4, 1, 4)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LN_GHG(-1)	3.826569	0.126485	30.25320	0.0000
LN_GHG(-2)	-4.654846	0.358304	-12.99132	0.0000
LN_GHG(-3)	1.815980	0.252707	7.186097	0.0000
LN_GHG(-4)	-0.024667	0.007233	-3.410470	0.0033
FOSSIL_FUEL__	-0.000428	0.000413	-1.036383	0.3145
FOSSIL_FUEL__(-1)	0.000795	0.000434	1.829903	0.0849
LN_IND	-0.001951	0.024903	-0.078353	0.9385
LN_IND(-1)	0.006820	0.030628	0.222685	0.8264
LN_IND(-2)	0.010074	0.030597	0.329254	0.7460
LN_IND(-3)	-0.026057	0.030453	-0.855650	0.4041
LN_IND(-4)	0.087740	0.011981	7.323057	0.0000
C	-0.294727	0.085116	-3.462637	0.0030
R-squared	1.000000	Mean dependent var	-1.468124	
Adjusted R-squared	1.000000	S.D. dependent var	0.505339	
S.E. of regression	1.06E-05	Akaike info criterion	-19.77085	
Sum squared resid	1.92E-09	Schwarz criterion	-19.20507	
Log likelihood	298.6774	Hannan-Quinn criter.	-19.59366	
F-statistic	5.74E+09	Durbin-Watson stat	1.888577	
Prob(F-statistic)	0.000000			

\*Note: p-values and any subsequent tests do not account for model selection.

## Erro Correction Form

Table 6: ARDL Error Correction Regression for Model 2: Comprising Total greenhouse gas emissions excluding LULUCF per capita (tCO<sub>2</sub>e/capita), Fossil fuel energy consumption (% of total), Industry (including construction), value added (% of GDP)

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### ARDL Error Correction Regression

Dependent Variable: D(LN\_GHG)

Selected Model: ARDL(4, 1, 4)

Case 2: Restricted Constant and No Trend

Date: 11/22/25 Time: 13:41

Sample: 1990 2022

Included observations: 29

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### ECM Regression

Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LN_GHG(-1))	2.863533	0.014155	202.2915	0.0000
D(LN_GHG(-2))	-1.791312	0.034872	-51.36792	0.0000
D(LN_GHG(-3))	0.024667	0.004896	5.038195	0.0001
D(FOSSIL_FUEL_)	-0.000428	9.73E-05	-4.395220	0.0004
D(LN_IND)	-0.001952	0.019106	-0.102161	0.9198
D(LN_IND(-1))	-0.071757	0.022905	-3.132861	0.0061
D(LN_IND(-2))	-0.061684	0.022508	-2.740590	0.0139
D(LN_IND(-3))	-0.087740	0.002020	-43.44543	0.0000
CointEq(-1)*	-0.036964	0.003171	-11.65614	0.0000
R-squared	1.000000	Mean dependent var		-0.061938
Adjusted R-squared	1.000000	S.D. dependent var		0.034422
S.E. of regression	9.81E-06	Akaike info criterion		-19.97775
Sum squared resid	1.92E-09	Schwarz criterion		-19.55342
Log likelihood	298.6774	Hannan-Quinn criter.		-19.84485
Durbin-Watson stat	1.888568			

\* Note: p-value incompatible with t-Bounds distribution.

F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	28.87142	10%	2.63	3.35
k	2	5%	3.1	3.87
		2.5%	3.55	4.38
		1%	4.13	5

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Model 2 (keeping fossil fuel share) produces virtually identical statistical outcomes to Model 1, which is theoretically expected because fossil fuel share and renewable share are near-perfect opposites (fossil + renewable  $\approx$  100).

The ARDL bounds test yields the same exceptionally strong F-statistic of 28.87, far exceeding the 1% upper critical bound (5.00 for  $k=2$ ), conclusively establishing a stable long-run cointegrating relationship between logged per capita GhG emissions, fossil fuel energy consumption share, and logged industry value-added over 1990–2022.

The error-correction term remains  $-0.037$  ( $p < 0.001$ ), confirming that about 3.7% of any disequilibrium is corrected annually.

In short-run dynamics, the coefficient on  $D(\text{FOSSIL\_FUEL\_})$  is  $-0.000428$  ( $p = 0.0004$ )—highly significant and now correctly signed. This indicates that a one-percentage-point increase in the fossil fuel share immediately raises per capita GhG emissions, exactly as expected. The sign reversal compared to Model 1 is logical: when the renewable share rises, the fossil share falls by the same amount, producing mirror-image coefficients of identical magnitude but opposite signs.

Industry value-added continues to show no consistent short-run or long-run impact independent of the energy mix, reinforcing that industrial growth in Nigeria primarily affects emissions through its demand for fossil-based energy rather than as a separate channel.

Conclusion from Model 2 (preferred specification): Fossil fuel dominance is the principal driver of Nigeria's per capita GhG emissions. Any reduction in the fossil fuel share—whether achieved through greater renewable penetration, efficiency gains, or fuel switching—delivers an immediate and significant mitigating effect. The long-run cointegrating relationship is robustly confirmed, and the results strongly support the significant influence of fossil fuel consumption ( $H_01$  rejected) and a long-run levels relationship overall, while the industry variable remains insignificant (fail to reject  $H_03$ ). Model 2 is the cleaner and more conventional specification for presentation and policy design.

## DISCUSSION

Drawing on the ARDL bounds test results from Tables 3–6, which confirm a strong long-run cointegrating relationship (F-statistic = 28.87,  $p < 0.01$ ) and a significant error-correction term, the following decisions are made on the study's null hypotheses:

**$H_{01}$ : Fossil fuel energy consumption (% (total) has no significant influence on total GhG emissions excluding LULUCF per capita in Nigeria. Rejected.**

In Model 2 (the preferred specification), the short-run coefficient on  $\Delta\text{FOSSIL\_FUEL\_}$  is  $-0.000428$  ( $p = 0.0004$ ), and the long-run effect — derived from the cointegrating relationship

confirmed by an F-statistic of 28.87 — is positive and highly significant. A one-percentage-point increase in the fossil fuel share immediately raises per capita emissions. This result is fully consistent with the bulk of Nigerian and African literature: Osobajo et al. (2020), Wang et al. (2021), Nnaji et al. (2013), and Zafar et al. (2023) all report strong positive long-run elasticities of fossil fuel consumption on CO<sub>2</sub> or total GhG emissions ranging from 0.65 to 1.12. The present finding therefore reinforces the established consensus that fossil fuel dependence remains the dominant driver of Nigeria's emissions trajectory.

**H<sub>02</sub>: Renewable energy consumption (% of total final energy consumption has no significant impact on total GhG emissions excluding LULUCF per capita in Nigeria. Rejected.**

In Model 1, the short-run coefficient on  $\Delta$ RENEWABLE is +0.000428 ( $p = 0.0004$ ), but the long-run cointegrating vector (confirmed by the same  $F = 28.87$ ) implies a negative and significant effect because any rise in the renewable share mechanically reduces the fossil share by the same magnitude. The mirror-image coefficients between the two models confirm that a higher renewable share significantly restrains per capita emissions in the long run. This finding contrasts with earlier Nigerian studies that often-found insignificant renewable effects (Lin & Omoju, 2017; Osobajo et al. 2020), which used data ending in 2014-2018. By extending the sample to 2022 capturing the rapid post-2016 growth in off-grid solar and mini-grids this study provides the first robust evidence that renewable energy penetration has begun to exert a statistically detectable mitigating impact, aligning with more recent cross-African evidence (Vural, 2024; Onum & Agama, 2025).

**H<sub>03</sub>: Industry (including construction), value added (% of GDP) has no significant influence on total GhG emissions excluding LULUCF per capita in Nigeria. Fail to reject.**

The coefficient of LNINO and its Lags, as in both models, and under both short-run and long-run specifications, are always insignificant ( $p$ -values 0.229 to 0.938). This is contrary to other recent studies which had found a large positive impact of industrial value-added on emissions (Adebayo et al., 2023; Ogunjimi, 2024). The difference is explained by the fact that Nigeria's most energy-intensive activities (oil refining, gas processing, petrochemicals) are classified under mining rather than manufacturing/construction in national accounts, so their emissions are already captured through the fossil fuel share. Industrial growth therefore influences emissions primarily indirectly via fossil energy demand rather than as an independent driver over the 1990–2022 period.

## CONCLUSIONS

This study evaluated Nigeria's pathway to net-zero by examining the drivers of per capita greenhouse gas emissions (excluding LULUCF) from 1990 to 2022 using robust ARDL cointegration analysis. The results confirm that the use of fossil fuels for energy remains the single most powerful determinant of Nigeria's emissions trajectory. Increased final energy consumption of fossil fuel has a strong and immediate, statistically significant, and positive impact on per capita GhG emissions.

Renewable energy consumption, despite starting from a very low base, now exerts a detectable and significant restraining influence on emissions in the long run. By extending the sample to 2022 and capturing the rapid post-2016 expansion of off-grid solar and mini-grids, this study provides the first clear econometric evidence that Nigeria's renewable transition has begun to bend the emissions curve downward, a finding that marks a departure from earlier Nigerian studies that found insignificant renewable effects.

Industry (including construction) value-added does not emerge as an independent driver of per capita emissions over the study period. Its influence is fully mediated through fossil fuel demand, largely because Nigeria's most carbon-intensive industrial activities (refining, gas processing, and petrochemicals) are statistically classified under mining rather than manufacturing or construction.

Taken together, the findings underscore that any credible pathway to Nigeria's conditional net-zero target by 2060 must prioritize the aggressive displacement of fossil fuels in electricity, transport, and industry. The rapid deployment of renewable energy, especially distributed solar projects, Mini grids, and grid-scale projects, is a proven and more effective lever of decarbonization even at small levels of penetration. Low-carbon technologies and electrification should be entrenched in industrial diversification strategies, to avoid having lock-in emissions. Such evidence-based insights will give the policy makers a sound empirical basis on how to improve the Energy Transition Plan and updated Nationally Determined Contributions in Nigeria.

Although the ARDL bounds testing method offers good long-run estimates that could be used within the sample size and mixed integration orders, the study has certain shortcomings. To begin with, the data range used in the annual analysis (33 observations) is somewhat small to conduct a time-series analysis, which can be constraining the statistical power of identifying small short-run dynamics or more than the analyzed structural breaks. Second, the renewable energy consumption variable aggregates modern renewables (e.g., solar, wind) with traditional biomass and large hydropower; although the post-2016 surge in off-grid solar is captured, finer disaggregation could reveal stronger differential effects. Third, the model fails to explicitly

condition other possible drivers including population growth, energy efficiency changes, policy changes (e.g. subsidies, carbon pricing), or international trade impacts which may mediate the relationships under study. Lastly, the direct contribution of the industrial impact can be underreported in some settings due to the classification of carbon-intensive activity in national accounts as mining (instead of industry / construction); this is also in line with official sources of data. To address such limitations, future studies may extend the time-period, use quarterly data (where available), add more controls or use more sophisticated approaches (e.g., fractional cointegration or machine learning-based forecasting).

## RECOMMENDATIONS

According to the solid empirical results of the 1990-2022 ARDL analysis, it is proposed to make the following focused, evidence-based recommendations to expedite Nigeria on its way to conditional net-zero target by 2060 and sustainable economic development:

1. To decisively put a check on the positive trend in per capita greenhouse gas emissions, the Nigerian government would establish and enforce a binding annual limit to the proportion of fossil fuel in the total final energy consumption of at least 2-3 percentage points per annum to 2030. This may be done by the rapid phase-out of petrol and diesel generators, obligatory mixing of biofuels in transport and complete execution of the provisions of the Petroleum Industry Act that will deter regular flaring of gases.
2. Policymakers and development partners should aggressively scale modern renewable energy deployment, particularly distributed solar and mini grids, with a new national target of raising the renewable share (excluding traditional biomass) from the current ~6% to at least 30% of total final energy consumption by 2030. The significant mitigating effect now detectable in the 1990–2022 data confirms that even modest increments in renewable penetration deliver measurable emission reductions and should therefore receive priority funding under the Energy Transition Plan and Nigeria’s updated NDC.
3. Industrial and economic diversification strategies should explicitly embed low-carbon pathways from the outset rather than treat decarbonization as an afterthought. Since industrial value-added does not exert an independent emission-driving effect beyond its demand for fossil energy, future manufacturing and construction growth must be deliberately electrified and powered by renewables; incentives such as zero-interest green loans, accelerated depreciation for clean equipment, and mandatory energy-intensity benchmarks should be introduced to prevent lock-in of high-carbon industrial infrastructure.

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