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Do Changes in Fossil Fuel Usage and Output Predict Changes in CO_2 Emissions? A Linear and Nonlinear Empirical Evidence for Nigeria

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Abstract

Studies have shown that changes in fossil fuel usage and output are strong predictors of changes in CO2 emissions. Nigeria, a major oil producer, is experiencing an energy crisis marked by the abolition of fuel subsidies, a decision that is shaking up the country's economic landscape. Fossil fuels are crucial for global economic activity, powering industries and transportation. Still, their extraction, transport, and combustion contribute significantly to greenhouse gas emissions and climate change. This study investigates the relationship between fossil fuel consumption, economic growth, and CO2 emissions in Nigeria, utilising annual time series data from 1981 to 2021. It employed the linear and nonlinear autoregressive distributed lag (ARDL & NARDL) models. The bounds tests indicate no long-run relationship between the variables, indicating no stable equilibrium. In the short run, the results also revealed that a 1% increase in output leads to a 0.27% increase in carbon dioxide emissions: economic activities, on average, generate a moderate increase in CO2 emissions for each percentage point of economic growth, suggesting a combination of policy and technological interventions is needed to mitigate the environmental impact. This includes transitioning to renewable energy, implementing carbon pricing mechanisms, and investing in research and development of carbon capture technologies. The bound test results suggest that policies aimed at reducing emissions or promoting the use fossil fuel may not necessarily have a predictable or sustained impact on the Nigerian economy. This implies that current economic systems and processes are not particularly efficient in terms of emissions. The study recommends a holistic energy planning approach, including investment in energy infrastructure, which might be more effective in driving economic growth than solely focusing on emission reduction or fossil fuel consumption.

Keywords: CO2 emissions, Energy consumption, Economic growth, ARDL Model
JEL Classification: C22, Q44, Q50

Contribution to/Originality Knowledge

1.0 Introduction

The Nigerian economy has experienced phenomenal growth over the last decade, averaging about 2.38% in 2022. Being the most populous nation in Africa, with an estimated population of over 218,541,212 in 2022 (O'Neilli, 2024). This rapid growth has made this country the fastest-growing economy among developing nations. However, with this strong economic growth, Nigeria's demand for energy is increasing, just as pollutant emissions are (Shuaibu & Oyinlola, 2013). This is because an attempt to achieve a higher growth rate and development is usually at the expense of the environment. After all, it can lead to increased consumption and more carbon dioxide emissions. The relationship between carbon dioxide emissions and the economy is complex and can have both positive and negative effects. Some studies have found a positive relationship between carbon dioxide emissions and economic growth. For example, a study in Nigeria found that rising carbon dioxide emissions had a positive impact on economic growth. However, other studies have found that carbon dioxide emissions negatively affect economic growth (Espoir & Sunge, 2021).

Therefore, economic growth has been closely linked to increased carbon dioxide (CO_2) emissions and energy consumption. This leads to the opinion that a more prosperous world implies negative impacts on the natural environment and climate. (González-Álvarez & Montañés, 2023,). To date, there have been lively academic debates about the possibility of achieving a complete decoupling of emissions and growth[1] (Balcilar, Bekun, & Uzuner, 2019; Bekun, 2022; Bekun & Agboola, 2019; Hubacek, Chen, Feng, Wiedmann, & Shan, 2021).

Specifically, since the pioneering work of Kraft and Kraft (1978), the relationship between energy consumption and economic growth has become a topic of considerable interest in environmental science and energy economics (Wang et al., 2016). Over the last few decades, studies such as Glasure (2002), Ghali and El-Sakka (2004), Akinlo (2008), Apergis and Payne (2009), among others have confirmed the existence of a strong historical correlation between these two variables, with most empirical results indicating that economic growth can indeed cause increases in energy consumption. Indeed, energy consumption is also generally recognised as the primary factor influencing CO_2 emissions. Many recent studies have examined the relationship between energy consumption, CO_2 emissions, and economic growth, covering various countries and regions. However, the findings of these studies have emerged as a key research issue, forming the focus of numerous theoretical explorations and a large number of empirical investigations in recent years.

Fossil fuels have played a significant role in shaping human civilisation to its present-day form. Humans have used energy in various forms since prehistoric times for survival, development, and recreation. Overall, economic development is invariably linked with energy use and, therefore, fossil fuels. Nigeria, a major oil producer, is experiencing an energy crisis marked by the abolition of fuel subsidies, a decision that is significantly impacting the country's economic landscape. The reform has led to a sharp rise in petrol prices, from 610 to 855 Naira per litre at Nigerian National Petroleum Company Limited (NNPC) stations, with prices increasing to 1,200 Naira at private stations.

However, these new measures, perceived as a necessary economic adjustment, are generating tensions on the local market, directly affecting the cost of goods and services (EnergyNews, 2025). Fossil fuels (coal, oil, and natural gas) are the backbone of modern industrial economies, providing energy for various sectors like transportation, manufacturing, and electricity generation. However, their extraction, transport, and combustion contribute significantly to

[1] The extent to which the adoption of clean energy technologies can allow emissions to decline as economic growth continues

greenhouse gas emissions and climate change. Therefore, economic activity, often fueled by fossil fuels, is generally associated with increased carbon dioxide (CO2) emissions. However, the relationship is complex and can vary depending on factors like energy efficiency and technological advancements (Hoa et al., 2024).

Although numerous studies have investigated the relationship between fossil fuel usage, output (often measured by GDP), and CO2 emissions in Nigeria, the findings consistently highlight a strong correlation. Some research focuses on the causal relationship between electricity supply, fossil fuel consumption, CO2 emissions, and economic growth. Other studies examine the long-run relationship between fossil fuel consumption and CO2 emissions; the findings demonstrate that fossil fuel use enhances carbon emissions. Additionally, some research explores the determinants of CO2 emissions in Nigeria, identifying factors like fossil fuel demand, economic growth, and agricultural practices. Ogundipe et al. (2020) found that approximately 80% of carbon emissions in Nigeria are directly attributed to fossil fuel combustion, and that pollution levels increase with income and population density. Investigating the relationship between fossil fuels, economic growth, and carbon dioxide emissions in Nigeria is crucial for understanding the country's environmental and economic sustainability. As a major oil producer, Nigeria is said to rely heavily on fossil fuels for energy, which directly contributes to high CO2 emissions. This research aims to determine the extent to which Nigeria's economic growth, driven by fossil fuels, is influencing CO2 emissions and how these emissions, in turn, impact economic development. Specifically, this study examines whether fossil fuels, as a source of energy and driver of economic growth, are associated with carbon dioxide emissions in Nigeria. To achieve this, it is first necessary to look at the past and present dynamics of fossil fuel use and economic growth. The remainder of the study is organised as follows. Section 2 presents the literature review, which encompasses the existing knowledge, while Section 3 describes the methodology. Section 4 presents the data, empirical results, and discussion. Finally, Section 5 presents the conclusions and identifies the economic implications.

2.0 Literature Review

Carbon dioxide emissions, often referred to as CO_2 emissions, are primarily caused by human activities, notably the burning of fossil fuels and industrial processes like cement production (WB, 2025). On the other hand, fossil fuels are extensively used for energy production, transportation, and various industrial processes. They are primarily used in power plants to generate electricity, power vehicles and aircraft, and as feedstocks for various manufacturing processes[2]. Economic growth and output are intertwined concepts. Economic growth refers to the increase in an economy's production of goods and services over time, typically measured by the change in Gross Domestic Product (GDP). Output, on the other hand, refers to the total

[2] While CO2 emissions include carbon dioxide produced during the consumption of solid, liquid, and gas fuels and gas flaring, Fossil fuels are formed from the decomposition of buried carbon-based organisms that died millions of years ago. They create carbon-rich deposits that are extracted and burned for energy. They are non-renewable and currently supply around 80% of the world’s energy. There are three types of fossil fuel – coal, oil and gas (ClientEarth, 2025)

value of goods and services produced in a specific period (Grimsley, 2025). Therefore, increases in an economy's output drive economic growth.

The relationship between fossil fuel usage and CO2 emissions is a core concept in climate science and economics. The primary theory is that the combustion of fossil fuels releases stored carbon into the atmosphere, leading to increased CO2 concentrations and a corresponding rise in global temperatures. Furthermore, the "carbon curse" theory suggests that nations rich in fossil fuels may rely on these resources heavily, leading to higher emissions (Khan et al., 2022). "Resource curse" is a term used to describe the notion that nations with abundant natural resources are often experiencing slower economic growth than those with fewer resources (Sachs & Warner, 1995). The theory focuses on the institutional and economic dimensions of resource abundance but neglects its potential environmental effect. However, literature on environmental degradation mostly neglects the link between resources and pollution. The Environmental Kuznets Curve (EKC) posits that as economic growth increases, CO2 emissions rise initially, but then decrease at higher levels of economic development (Otim et al., 2023).

The literature on the relationship between carbon dioxide emissions, energy usage, and output or economic growth has grown rapidly in recent years. The majority of the studies initially focused on the relationship of any combination of environmental effects, the economy, and energy, with these three variables proxied mainly by CO2, the GDP, and energy consumption, respectively (González-Álvarez & Montañés, 2023,). In addition, the list of articles on the subject is extensive and varied, with many focusing on different countries or groups of countries, as well as various analytical techniques. The following studies examine the relationship between energy consumption, economic growth, and carbon emissions.

Akorede and Afroz (2020) relate urbanization, CO2 emissions, economic growth and energy consumption in Nigeria between 1970 and 2017 using the ARDL model approach. The key findings revealed that in the short run, energy consumption and the previous lag in economic growth have a positive and significant impact on carbon dioxide emissions in Nigeria. Only the urban population has a negative but significant impact on CO2 emissions in Nigeria. In the long run, however, urbanisation remains statistically significant but negative, while energy consumption and economic growth continue to have a positive and significant impact on CO2 emissions. Yusuf (2023) examines the dynamic effect of energy consumption, economic growth, international trade, and urbanization on environmental degradation in Nigeria from 1980 to 2020. The study employed the ARDL technique in the presence of structural breaks. The empirical findings support the existence of the environmental Kuznets curve hypothesis for Nigeria in the long and short run. Energy consumption and total imports exacerbate environmental deterioration in both the long and short run, whereas total exports improve environmental quality in both the long and short run.

Gershon et al. (2024) investigate the nexus between energy consumption, economic growth, and carbon emissions in 19 selected African countries, including Nigeria. The study employed static panel estimation techniques, including Random Effects (RE) and Fixed Effects (FE), as well as Feasible Generalised Least Squares (FGLS). The findings revealed that an increase in energy consumption has a positive impact on economic growth, but an adverse effect on carbon emissions. Specifically, energy consumption has a greater positive impact on economic growth than its adverse environmental effects. Furthermore, economic growth helps mitigate or reduce the negative environmental impact of energy usage. Emonena and Osifo (2024) empirically investigate the relationship between carbon emissions and economic growth in Nigeria, employing cointegration and dynamic causality analysis with annual time-series data spanning 1981 to 2021. The findings revealed a link between CO_2 emissions and economic growth, but a negative and statistically insignificant relationship exists between CO_2 emissions and long-term economic growth.

Benjamin et al. (2023) analysed the relationship between fossil energy consumption, carbon dioxide emissions, and the adult mortality rate in Nigeria between 1980 and 2019 using the ARDL technique. The results indicate that fossil energy consumption reduces adult mortality rates in the short run, while CO2 emissions increase adult mortality rates in both the short and long run. Tijani et al. (2023) investigate the relationship between energy efficiency, carbon emissions, and economic growth in Nigeria from 1980 to 2021, employing the ARDL bounds testing framework and the Granger causality test. The results revealed that economic growth and energy consumption significantly increase energy-related emissions. Zakari et al. (2022) investigate the impact of carbon dioxide emissions and financial development on economic growth in Nigeria between 1981 and 2021 using the ARDL bound testing technique. The results revealed long-run cointegration among the variables, indicating that rising emissions have a significant and positive impact on economic growth. Additionally, openness and financial development have a significant and positive effect on the growth of the Nigerian economy. Ogbeide and Ugbogbo (2022) empirically assessed carbon footprint and economic performance in Nigeria between 1980 and 2021 using the General Method of Moments (GMM) estimation method. The key findings revealed that carbon emissions have an inverse relationship with economic growth. Electricity consumption, trade openness, and human capital investment exerted a positive impact on Nigeria's economic growth, although none of these factors was significant, except for trade openness.

Ezenwa et al. (2021) analysed the relationship between economic growth, renewable energy consumption, and CO2 pollution in Nigeria between 1990 and 2015 using the Vector Error Correction model (VECM). The findings reveal bi-directional causality between renewable energy consumption (REC) and economic growth (GDP); REC positively Granger-causes GDP in both the short and long run, while GDP has an adverse effect on REC in the short run. Adebayo et al. (2021) examine the asymmetric impact of international trade on consumption-based carbon dioxide emissions in the MINT countries (Mexico, Indonesia, Nigeria, and Turkey) from 1990 to 2018 using the Nonlinear ARDL approach. The results revealed positive (negative) shocks in imports increase (decrease) CO2 emissions, while positive (negative) shocks in exports decrease (increase) CO2 emissions, and also confirm the existence of the EKC hypothesis in all the MINT nations. Omodero and Uwalomwa (2021) investigate the influence of energy consumption and carbon dioxide emission on economic growth between 2008 and 2009 using Multiple regression techniques to assess the impact of Electricity, CO2, primary energy, and total labour force on GDP. Out of the four energy sources examined, Electricity is found to have no significant impact on Nigeria's economic growth. The CO2 emissions are positively significant, implying that the economy is growing at a high level of environmental pollution. The primary energy consumption put forth a substantial harmful effect on economic progress, while the total labour force has a strong significant affirmative impression on fiscal progression.

Ogundipe et al. (2020) investigate the effect of fossil fuel consumption on environmental quality in Nigeria between 1970 and 2017 using the Johansen cointegration test and the Vector Error Correction Model. The result reveals that about 80% of carbon emissions in Nigeria are directly a consequence of fossil fuel combustion. Bernard et al. (2018) examine the relationship between energy consumption, CO2 emissions, and economic growth in Nigeria from 1981 to 2015, using the Zivot-Andrews unit root test and the ARDL model. The results revealed a long-run relationship between economic growth (RGDP) and capital, Labour, energy consumption, and CO2 emissions; energy consumption, capital, and labour contribute positively to economic growth, while CO2 emissions contribute negatively to economic growth in the short run. Alege et al. (2016) investigate the relationship between Pollutant Emissions, Energy Consumption, and economic growth in Nigeria between 1970 and 2013, using the Johansen Cointegration and Granger Causality Tests. The findings revealed the existence of a unique cointegrating vector, and the normalized long-run estimates showed that a clean energy source (electricity) mitigates the atmospheric concentration of carbon dioxide (CO2) emissions. Additionally, the results indicated the existence of unidirectional causation running from fossil fuel to CO2 emissions and gross domestic product (GDP) per capita.

Chindo et al. (2014) investigate the relationship between energy consumption, CO2 emissions, and GDP in Nigeria between 1977 and 2008, and between 1965 and 2008, using the ARDL approach to cointegration. The results revealed a long-run relationship between energy consumption, CO2 emissions, and GDP. Both in the long run and short run, CO2 emissions have been found to have a significant positive impact on GDP. Similarly, Chindo (2014) examines the causal relationship between energy consumption, CO2 emissions, and economic growth. It employed a modified version of the Granger causality test suggested by Toda and Yamamoto. The findings revealed that unidirectional causality runs from CO2 emissions to economic growth, and from energy consumption to CO2 emissions, with bi-directional causality between energy consumption and economic growth. Yusuf (2014) examines the impact of Energy consumption and carbon emissions on economic growth in Nigeria from 1981 to 2011 using the restricted error correction model (VAR), Impulse Response function, and Granger causality analysis. The results revealed that a long-run relationship exists among the variables, and electricity contributes significantly to economic growth; bidirectional causality between electricity consumption and economic growth; unidirectional causality running from energy use kt of oil to carbon emission. Akpan and Akpan (2012) examine the relationship between electricity consumption, carbon emissions, and economic growth in Nigeria from 1970 to 2008 using the Multivariate Vector Error Correction (VECM) framework. The results revealed that, in the long run, economic growth is associated with increased carbon emissions, while an increase in electricity consumption leads to an increase in carbon emissions.

3.0 Research Methodology

The methodological section comprises five aspects of the research process. It begins with the data sampled, variables, sources, measurement and preliminary testing procedure followed by model specification and estimation techniques. It employs descriptive statistics and stochastic analysis to summarize and describe the main features of a dataset in a logical, meaningful, and efficient way. The essence is to report the basic five questions of who, what, where, why, when, how, and to what extent.

3.1 Sources of Data and Measurement

Table 1: Data Description and Sources

Variable	Notations	Data source & Measurement
CO2 Emissions including land-use change	CO2	Global Carbon Budget (2024), Our World in Data: CO2 emissions are measured in various units, such as kilograms (kg) or metric tons (t), and are often converted to CO2 equivalent (CO2e) to account for different greenhouse gases.
Fossil Energy usage	EC	US Energy Information Administration (2023), Energy Institute – Statistical Review of World Energy (2024), & Our World in Data: Fossil fuel usage is typically measured in terms of energy consumption, often expressed in terawatt-hours (TWh), or kilowatt-hours (kWh). It is measured as the average consumption of energy from coal, oil, and gas.
Output	GDP	World Bank and OECD (2025), Our World in Data: GDP, or Gross Domestic Product, can be measured using three primary methods: the production (output) approach, the expenditure approach, and the income approach.

Source: Author's Compilation

3.2 Model Specification

The second part presented the three model specifications for annual time series data that consist of yearly observations between 1981 and 2021. The functional as well as econometric specifications of the study model underestimation for Nigeria are given below:

$$CO_2 = f\left(EC, GDP\right) \quad (1)$$

$$CO_{2t} = \eta + \pi_1 CO_{2_{t-1}} + \pi_2 EC_{t-1} + \pi_3 GDP_{t-1} + \mu_t \quad (2)$$

Where: CO_2, and GDP represent the carbon dioxide emission, energy consumption, and economic growth respectively.

Ƞ = constant parameter

μ = current error term

π_1, π_2, π_3 = Coefficient or model parameters

$CO2_t$ = Current value of carbon dioxide emission

$CO2_{t-1}$ = One lagged value of carbon dioxide emission

EC_{t-1} = One lagged value of energy consumption

GDP_(t-1)= One lagged value of GDP

3.4 Tools of Analysis

3.4.1 Descriptive

Table 1 provides an overview of the time series data from 1981 to 2021 and measures (i.e. central tendency, variability, and distribution) without making any assumptions beyond the data itself. A valid and reliable descriptive and stochastic analysis of the basic features makes it easier to understand the data's main characteristics such as the identification of potential outliers or anomalies; test for the normality or homogeneity of variance, among others, assumptions about the data; check for the data's readiness for further analysis to summarize and communicate the research findings clearly and concisely.

3.4.2 Unit Root Test

To decide with regards to the most appropriate model specification and estimation techniques to use and conduct, respectively, for the relationship between the CO2, EC, and GDP, the time series data need to be examined for their stationarity properties even though the application of some methods may not require formal unit root test for the variables but the test is performed just to be sure that none of the series is stationary at second difference i.e. I (2). Additionally, it is crucial to determine whether the series exhibits stationarity or non-stationarity to prevent spurious regression. Consequently, the study conducts unit root tests using Augmented Dickey-Fuller (ADF) to ensure that none of the series is stationary at the second difference i.e. I (2).

3.4.3 Cointegration Test

To determine whether there is a long-term correlation between fossil fuel usage, output, and carbon dioxide emissions, the study employs a cointegration test. It identifies scenarios where two or more non-stationary time series are integrated in a way that prevents them from deviating from equilibrium in the long term. It is generally used to identify the degree of sensitivity of two variables to the same average value over a specified time period. Before its introduction, economists relied on linear regressions to find the relationship between several time series processes. However, Granger and Newbold (1974) argued that linear regression was an incorrect approach for analyzing time series due to the potential for producing spurious correlations[3].

Engle and Granger (1987) formalized the cointegrating vector approach. Their concept established that two or more non-stationary times series data are integrated in a way that they cannot move away from some equilibrium in the long term. The study argued against the use of linear regression to analyze the relationship between several time series variables, as detrending would not resolve the issue of spurious correlation. Instead, they recommended checking for cointegration of the non-stationary time series. There are several methods for

[3] A spurious correlation occurs when two or more associated variables are deemed causally related due to either a coincidence or an unknown third factor. A potential outcome is a misleading statistical relationship between multiple time series variables

testing cointegration[4], used to identify the long-term relationships between two or more sets of variables. This study employs two different but complementary estimation techniques – linear and nonlinear ARDL models – to investigate the dynamic relationship between CO2, EC, and GDP. The Autoregressive Distributed Lag (ARDL) model analyzes dynamic relationships, cointegration test, or the existence of a long-run relationship between CO2, EC, and GDP over time, and separates the short-run and long-run effects of EC and GDP on CO2.

3.4.4 The Linear ARDL Approach

The ARDL approach allows the inclusion of other models with dissimilar variables that take a diverse optimal number of lags. These problems lead to the direct estimation of the long-run parameters using unrestricted error correction models (UECM) that specify the inclusion of dynamics (Olokoyo et al., 2009). When an unrestricted dynamic model includes lagged and current values of dependent and independent variables then the model becomes an autoregressive distributed lag model. The bounds-testing approach together with the ADRL modeling approach to co-integration analysis developed by Pesaran et al. (2001), involves an ordinary least square estimation of an ECM of the following form:

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \alpha_2 X_{t-1} + \sum_{i-1}^{p-1} \beta_i \Delta Y_{t-1} + \sum_{i-1}^{q-1} \beta_i \Delta X_{t-1} + e_t \qquad (3)$$

In this expression, Δ is the first difference operator, α_0 is the constant, Y_t is the dependent variable (output), X_t is the independent variable, e_t is the error term, p and are the maximum lag orders, α_1 is the long-run relationship (elasticities) among the variables, and βi is the short-run relationship among the variables. One of the main benefits of expanding the ARDL is the existence of a long-run level relationship in an ECM framework between the dependent variable Y_t and the independent variable X_t that can be tested when it is not known whether the underlying independence is stationary, non-stationary, or mutually co-integrated with the ARDL model (Odhiambo, 2009).

3.4.5 Short-run Coefficient Estimation

The short-run elasticity will be estimated through a typical dynamic short-run function as specified below.

$$\Delta \ln CO2_t = l_0 + \sum_{j=1}^{2} \chi_j \Delta CO2_{t-1} + \sum_{j=1}^{2} \theta_j \Delta EC_{t-1} + \sum_{j=1}^{2} \pi_j \Delta GDP_{t-1} + \zeta ECT + \mu_t \qquad (4)$$

[4] These include the Engle-Granger Two-Step method, which begins by creating residuals based on the static regression and then tests the residuals for the presence of unit roots. It uses the Augmented Dickey-Fuller Test (ADF) or other tests to test for stationarity units in time series. If the time series is cointegrated, the Engle-Granger method will show the stationarity of the residuals. The second is the Johansen test, which allows for more than one cointegrating relationship

Where $\zeta ECT + \mu_t$ is the error correction term, which is equivalent to the lagged value of the error term from the equation (8), K is the number of lags used.

3.4.6 Long-run Elasticity Estimation

In this study, the long-run equilibrium function is specified as:

$$\Delta \ln CO2_t = l_0 + \alpha_1 \ln EC_t + \alpha_2 \ln GDP_t + \partial_t \quad (5)$$

Where ∂_t is the error term.

The test involves calculating an F-statistic and comparing it to critical bounds based on the estimated model. If the calculated F-statistic is higher than the upper critical bound, it suggests a strong likelihood of a long-run relationship between the variables. Conversely, if the F-statistic is lower than the lower critical bound, it indicates a lack of evidence for a long-run relationship. If a long-run relationship is established, the ARDL bounds test allows for the estimation of both long-run and short-run coefficients.

The long-run coefficients represent the equilibrium relationship between the variables, while the short-run coefficients capture the dynamic adjustments towards the long-run equilibrium. The statistically significant and negative sign of the ECT_{t-1} coefficient (ϑ) implies that any short-run disequilibrium among the dependent variable and some independent variables will converge back to the long-term equilibrium association. However, if a long-run relationship is not found in an ARDL model, it is generally not recommended to proceed with estimating short-run coefficients as the whole premise of the ARDL approach is to analyze the short-run dynamics within the context of a long-run equilibrium; without that equilibrium, the short-run estimates would not have a meaningful interpretation.

Additionally, to model the short- and long-run asymmetries for the asymmetric responses to changes and estimate the impact of positive and negative shocks separately, the study used the non-linear autoregressive distributed lag (NARDL) model.

3.4.7 The NARDL Approach Specification

The NARDL approach allows the investigation of the potential asymmetric impact of EC and GDP on Nigeria's CO2 in both the long and short-term spheres of time[5]. Shin et' al. (2014) developed NARDL by considering an asymmetric long-run regression:

$$y_t = \beta^+ x_t + \beta^- x_t + \mu_t \quad (6)$$

[5] The NARDL model has advantage over the linear ARDL model in at least three dimensions: it permits the underpinning variables of study to shift across period, can be applied to stationary and non-stationary time series vectors, and includes an error correction process or a mechanism that considers asymmetries in long-run co-integration. Therefore, the NARDL is compatible with retaining the variables under consideration in developing new structural analysis

$$\Delta x_t = V_t \tag{7}$$

Where:

y_t and x_t are scalar I_1 variables, and

x_t is decomposed as $x_t = x_0 + x_t^+ + x_t^-$

Where: x_t^+ and x_t^- are partial sum processes of positive and negative changes in x_t:

$$x_t^+ = \sum_{j=1}^{t} \Delta x_t^+ = \sum_{j=1}^{t} Max\left(\Delta x_j, 0\right), x_t^- = \sum_{j=1}^{t} \Delta x_t^- = \sum_{j=1}^{t} Max\left(\Delta x_j, 0\right) \tag{8}$$

The above provides modeling asymmetric cointegration with partial sum decompositions. Schorderet (2003) defines a stationary linear combination of the partial sum components:

$$z_t = \beta_0^+ y_t^+ + \beta_0^- y_t^- + \beta_1^+ y_t^+ + \beta_1^- y_t^- \tag{9}$$

If z_t is stationary, then y_t and x_t are 'asymmetrically cointegrated'. The standard linear (symmetric) cointegration is a special case of (4), obtained only if $\beta_0^+ = \beta_0^-$ and $\beta_1^+ = \beta_1^-$. Shin et' al. (2014) consider the case where the following restriction holds: $\beta_0^+ = \beta_0^- = \beta_0$. In expression (4), this implies that:

$$\beta^+ = \frac{\beta_0^-}{\beta_0}$$

And

$$\beta^- = \frac{\beta_0^+}{\beta_0}$$

$$y_t = \sum_{j=1}^{p} \varphi_j y_{t-1} \left(\theta_j^{+'} x_{t-1}^{+'} + \theta_j^{-'} x_{t-1}^{-'}\right) + \varepsilon_t \tag{10}$$

Where:

x_t is a k x 1 vector of multiple regressors, $x_t = x_0 + x_t^+ + x_t^-$, is the autoregressive parameter, $\theta_j^+ and\ \theta_j^+$ are the asymmetrically distributed lag parameters, and ε_t is an i.i.d. process with zero mean and constant variance, σ_ε^2.

Shin et al. (2014) considers x_t is decomposed into x_t^+ and x_t^- around zero, distinguishing between positive and negative changes in the rate of growth of x_t , They follow Pesaran et al. (2001) and write (5) in the error correction form as:

$$\begin{aligned}\Delta y_t &= py_{t-1} + \theta^{+'} x_{t-1}^{+} + \theta^{-'} x_{t-1}^{-} + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-1} + \sum_{j=1}^{q-1} \left(\phi_j^{+'} \Delta x_{t-j}^{+} + \phi_j^{-'} \Delta x_{t-j}^{-} \right) \\ &= p\zeta_{t-1} + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-1} + \sum_{j=1}^{q-1} \left(\phi_j^{+'} \Delta x_{t-j}^{+} + \phi_j^{-'} \Delta x_{t-j}^{-} \right)\end{aligned} \quad (11)$$

Where:

$$\rho = \sum_{j=1}^{p} \varphi_{j-1},\ Y_j = \sum_{i=j+1}^{p} \varphi_j \text{ for } j = 1, \ldots, \rho - 1,\ \theta^{+} = \sum_{j=0}^{p} \theta_j^{+},\ \theta^{-} = \sum_{j=1}^{q} \theta_j^{-},\ \varphi^{+} = \theta_0^{+}$$

$$\varphi_j^{+} = \sum_{i=j+1}^{q} \theta_j^{+},\ \text{for } j = 1, \ldots, q-1, \varphi_0^{-} = \theta_0^{-}, \varphi_j^{-} = \sum_{i=j+1}^{q} \theta_j^{-},\ \text{for } j = 1, \ldots, \rho - 1$$

and

$\zeta_t = y_t - \beta^{+'} x_t^{+} - \beta^{-'} x_t^{-}$, is the nonlinear ECM, where $\beta^{+} = -\theta^{+}/\rho$ and $\beta^{-} = -\theta^{-}/\rho$ are the associated asymmetric long-run parameters.

To deal with non-zero contemporaneous correlation between regressors and residuals in (6), Shin et' al. (2014) proposes the following reduced-form data generation process for Δx_t:

$$\Delta x_t = \sum_{j=1}^{q-1} \Lambda_j \Delta x_{t-j} + v_t \quad (12)$$

Where: v_t~i.i.d.$(0, \sum v)$, with $\sum v$ a $k\ x\ k$ positive definite covariance matrix. In terms of their focus on conditional modeling, they express ε_t in terms of $v_t$as:

$$\varepsilon_t = w' v_t + e_t = w' \left(\Delta x_t - \sum_{j=1}^{q=1} \Lambda_j \Delta x_{t-1} \right) + e_t \quad (13)$$

Where: $e_t$is correlated with $v_t$by construction. If we substitute (8) into (6) and rearrange, we obtain a nonlinear conditional ECM:

$$\Delta y_t = \rho \zeta_{t-1} + \sum_{j}^{p-1} \gamma_j \Delta y_{t-1} + \sum_{j=0}^{q-1} \left(\pi_j^{+'} \Delta_{t-j}^{+} + \pi_j^{-'} \Delta_{t-j}^{+} \right) + e_t \quad (14)$$

Where: $\pi_0^+ = \theta_0^+ + w$, $\pi_0^- = \theta_0^- + w$, $\pi_j^+ = \phi_j^+ + w'\Lambda_j$, and $\pi_j^- = \phi_j^- + w'\Lambda_j$, for $j = 1, \ldots\ldots, q-1$. Equation (9) corrects for the weak endogeneity of non-stationary explanatory variables, and the choice of lag structure frees the model from any residual correlation. The model explains both long-run and short-run asymmetries and can be estimated by OLS as it is linear in all parameters.

3.4.8 Post Estimation Tests

The post-estimation tests are diagnostic tools used after estimating a statistical or econometric model (like the ARDL model) to assess its validity and reliability. These tests are typically conducted to verify whether the model's assumptions are met, identify potential issues such as multicollinearity, heteroscedasticity, or omitted variables, and assess the model's goodness-of-fit. To examine serial correlation, heteroscedasticity, normality in error terms or residuals, and model specification and stability tests, the study conducts diagnostic tests, including the Lagrange Multiplier (LM), Breusch-Pagan-Godfrey, Jarque-Bera, and Ramsey RESET tests, as well as the CUSUM and CUSUM of squares tests.

4.0 Empirical Results and Discussion

4.1 Data Description

The annual data for CO2, energy consumption, and growth used in this study relate to the period 1981 to 2021. The descriptive analysis in Table 2 shows that the standard deviation values for all the variables indicate that these variables are comparatively distributed below their mean and median values. Except for CO2, which is negatively skewed and normally distributed, energy consumption and GDP are positively skewed and not normally distributed, as indicated by the skewness values and Jarque-Bera probability values, respectively, within the study period of 1981 to 2022. The correlation analysis reveals that EC and GDP positively correlate with CO2. The results indicate that an increase in any of the independent variables will cause an increase in CO2 and, more importantly, the correlation coefficients are 0.86 and 0.76 for CO2_EC and CO2_GDP, respectively.

Table 2: Descriptive Statistics and Correlation Matrix

Descriptive Statistics			
Statistics	**CO2**	**EC**	**GDP**
Mean	88007681	289.2435	205.2966
Median	89918616	248.4243	104.7390
Maximum	1.31E+08	543.7368	574.1838
Minimum	38857280	150.7351	27.75220
Std. Dev.	25703211	115.8825	176.3301
Skewness	-0.252710	0.868015	0.639623
Kurtosis	2.178345	2.448337	1.818242
Jarque-Bera (P-value)	1.589717 (0.451645)	5.668481 (0.058763)	5.181413 (0.074967)
Observations	41	41	41
Correlation Analysis: Spearman rank-order			
Variable	CO2	EC	GDP
CO2	1.000000		
EC	0.865505	1.000000	
GDP	0.769338	0.692160	1.000000

Source: Author’s Computation

4.2 Lag Selection Criterion

Table 3 reports the lag order selected by the criteria, namely, Hannan-Quinn Information Criterion (HQ), Schwarz Information Criterion (SC), Akaike Information Criterion (AIC), Final Prediction Error (FPE), and sequential modified LR test statistics - each test at 5% level – (LR). In all, the results revealed the optimal lag length of one out of a maximum of 3 lag lengths as selected by the five criteria.

Table 3: Lag Order Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-1141.933	NA	2.97e+22	60.25962	60.38891	60.30562
1	-1040.574	181.3796*	2.31e+20*	55.39861*	55.91575*	55.58261*
2	-1033.463	11.60221	2.57e+20	56.40301		55.82002
3	-1028.546	7.245175	3.27e+20	55.71296	57.00579	56.17294

Source: Author's Computation

4.3 Unit Root Test Results

To examine the integrating level of variables, the popular and standard test of ADF (Dickey & Fuller, 1981) is employed. The order of integration ADF tests has been used extensively in the literature. The ADF unit root test results presented in Table 4 clearly show that none of the variables included in the analysis is stationary in levels. However, the three series - CO2, EC, and GDP - become stationary after taking the first difference. Therefore, the results indicate that the three variables are stationary at first level difference and are said to be integrated of order one or more formally as I (1). The ARDL model is suitable when the variables are integrated of different orders, i.e., I(1) and I(0), or both, to allow for the testing of long-run relationships even if short-run dynamics are present .

Table 4: Augmented Dickey-Fuller (ADF) test

Variable			@ Level		@1st Difference	
			t-Statistic	**Prob.***	**t-Statistic**	**Prob.**
CO2	**ADF Test statistic**		-1.209086	0.6612	-7.613281	0.0000
	critical values:	1% level	-3.605593		-3.610453	
		5% level	-2.936942		-2.938987	
		10% level	-2.606857		-2.607932	
EC	**ADF Test statistic**		0.002698	0.9532	-7.291848	0.0000
	critical values:	1% level	-3.605593		-3.610453	
		5% level	-2.936942		-2.938987	
		10% level	-2.606857		-2.607932	
RGDP	**ADF Test statistic**		0.004455	0.9534	-4.281069	0.0016
	critical values:	1% level	-3.605593		-3.610453	
		5% level	-2.936942		-2.938987	
		10% level	-2.606857		-2.607932	

Source: Author's Computation

4.4 Model Estimation Results

After the test for the presence of unit root in the variables as presented in the previous section, it has given the way for the test of the possible existence of cointegration relationship among the series: carbon dioxide emission, energy consumption, and growth as reported in Table 5, 6 and 7 for DOLS, Linear ARDL model and Nonlinear ARDL model respectively. Therefore, the section empirically investigates whether a direct effect of energy consumption and economic growth on carbon dioxide emissions can be identified.

4.4.1 Linear ARDL Model Estimation

Table 5 presents the linear ARDL model results, the calculated F-statistic value of 2.210239 is less than the lower bound and the upper bound values at 1%, 5%, and 10% levels of significance, and at this point, the null hypothesis is accepted that there is no long-run relationship among the variables and reject the alternative hypothesis that there is cointegration relationship among the CO2 emission, economic growth, and GDP: that the explained (CO2 emissions) and explanatory (fossil fuel and output) variables are not moving together in the long-run.

Table 5: The ARDL bounds testing cointegration approach analysis

Test Statistic	**Value**					
F-statistic	2.210239					
	10%		**5%**		**1%**	
Sample Size	**I(0)**	**I(1)**	**I(0)**	**I(1)**	**I(0)**	**I(1)**
F-Statistic						
35	3.393	4.410	4.183	5.333	6.140	7.607
40	3.373	4.377	4.133	5.260	5.893	7.337
Asymptotic	3.170	4.140	3.790	4.850	5.150	6.360

Source: Author's Computation

Post Estimation Diagnostic Tests

Table 6 provides the post-estimation test results. It shows that, except for normality and CUSUMSQ diagnostic tests, all the linear regression model assumptions are satisfied in the short and long run. The Ramsey RESET test revealed that the model is correctly specified, meaning no omitted variables or functional form misspecifications exist.

Table 6: Post-estimation Test Results

Tests	**Statistic**	**Obs*R-squared**	**P-value**	**Prob. Chi-Square(2)**
Normality	15.82421		0.0004	
Serial Correlation	4.9662	1.775435	0.1199	0.0835
Heteroscedasticity	1.375827	6.731193	0.2578	0.2414
Ramsey RESET	0.669249		0.4192	
CUSUM	Stable			
CUSUMSQ	Unstable			

Source: Author's Computation

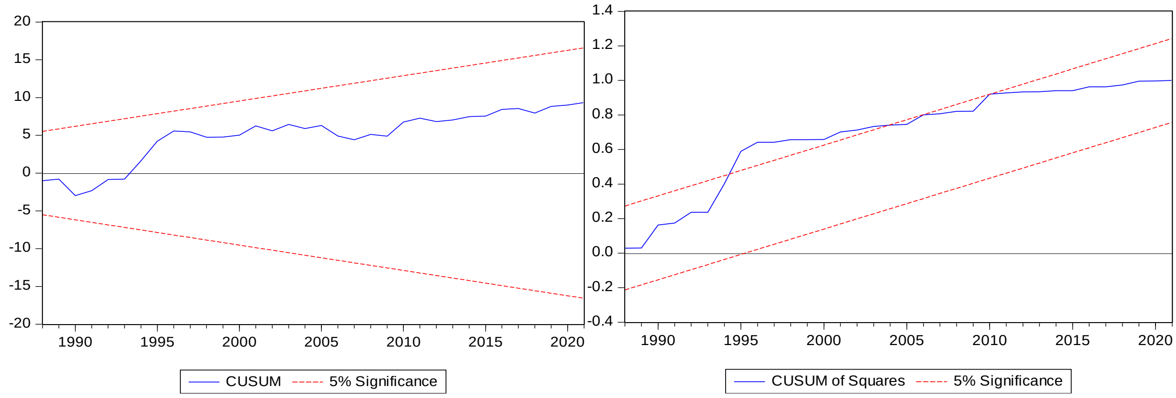

Figure 3: CUSUM & CUSUM of squares stability tests

ARDL (1,1,1) Model Short-run Results

From the ARDL results, there is clear evidence of no cointegration among variables. Therefore, including an Error Correction Mechanism (ECM) term in the short-run regression is not appropriate. An ECM is used to capture the short-run adjustment towards a long-run equilibrium relationship established by cointegration. Without cointegration, there is no long-run equilibrium to adjust towards, so an ECM term would be misinterpretable. But the lack of cointegration does not rule out short-term causal relationships between these variables. Table 7 shows the short-run results of the model. The results indicate that a 1% increase in economic growth has a positive, statistically significant effect at the 10% level on carbon dioxide emissions, whereas the effect of fossil energy appears insignificant. An increase in economic growth is expected to result in a 0.27% rise in carbon dioxide emissions.

Table 7: ARDL (1,1,1) Short-run results

Dependent Variable: LCO2				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.***
Long-run results				
C	5.012078	1.889898	2.652035	0.0118**
D(LEC)	0.303093	0.205733	1.473233	0.1494
D(LGDP)	0.266458	0.137189	1.942274	0.0600***
R-squared	0.805408			
Adjusted R-squared	0.776792			
F-statistic (Prob)	28.14497 (0.0000)			
Durbin-Watson stat	1.858254			

Note: *, **, *** represents significant level at 1%, 5%, and 10%, respectively

Source: Author's Computation (2024)

4.4.2 The Non-Linear ARDL Model

The standard ARDL model is based on the assumption of linearity and does not account for the non-linear adjustment process. In these situations, however, the relationship between CO2 emission, fossil fuel, and output is considered non-linear. Accordingly, Table 8 provides the details of the results from the nonlinear estimation. The results also revealed no cointegration between CO2 emissions, fossil fuel usage, and output, as the F-statistic is lower than the critical values at both the lower and upper bounds.

Table 8: Bound Test for Asymmetric Cointegration and Diagnostic Test Results

F-Bounds Test				
Test Statistic	**Value**	**Signifi.**	**I(0)**	**I(1)**
			Asymptotic: n=1000	
F-statistic	2.376915	10%	2.45	3.52
k	4	5%	2.86	4.01
		2.5%	3.25	4.49
		1%	3.74	5.06

Nonlinear ARDL Model Post Estimation Diagnostic Tests				
Tests	**Statistic/Version**	**Obs*R-squared**	**P-value**	**Prob. Chi-Square(2)**
Normality	1.879305		0.390959	
Serial Correlation	0.506026	1.409038	0.6085	0.4943
Heteroscedasticity	0.688976	6.870036	0.7129	0.6506
CUSUM	Stable			
CUSUMSQ	Stable			

Source: Author's Computation (2024)

Post Estimation Diagnostic Check

The diagnostic test results rejected the null hypothesis in all the cases. Additionally, the study applied CUSUM and CUSUMSQ tests for the estimated model stability; the results suggest the parameters' stability. Figure 4 demonstrates a lack of coefficient instability because the residuals and residual squares exist within the significance level's critical bounds at 5%.

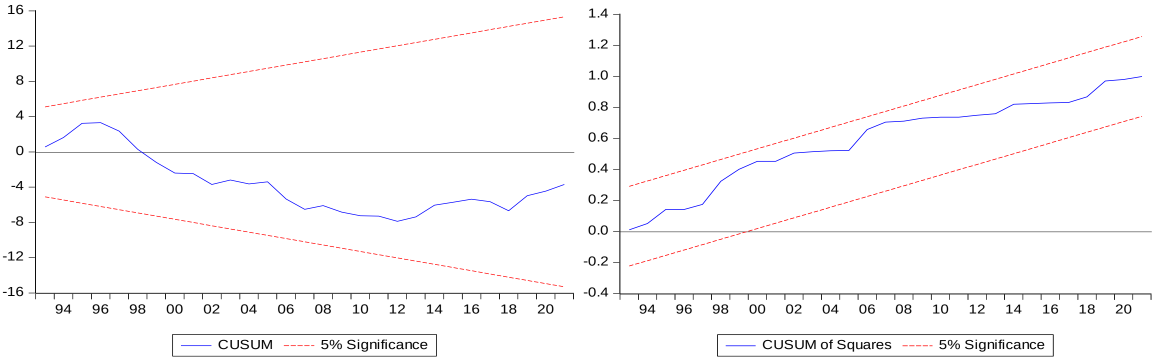

Figure 4: CUSUM and CUSUM of square stability tests

4.4.3 Summary of Key Findings

This study utilizes annual time series data from 1981 to 2021 to examine the relationship between fossil energy consumption, economic growth, and Nigeria's CO2 emissions. To achieve this, given that the linear and non-linear ARDL approaches apply to variables integrated of orders zero and one, the variables became stationary after the first difference when the ADF test was applied. Therefore, the symmetric and asymmetric ARDL model co-integration approaches are considered. Although the linear ARDL short-run results indicate that a 1% increase in economic growth has a positive, statistically significant effect at the 10% level on carbon dioxide emissions, the effect of fossil energy appears insignificant. However, the linear and nonlinear ARDL results revealed no long-run equilibrium relationship among the variables. However, some existing studies have found that energy consumption does not affect CO2 emissions or economic growth (Inal, 2022), implying that there might not be a stable, long-term relationship between the two variables. For example, Emonena and Osifo (2024) revealed a link between CO_2 emissions and economic growth in Nigeria, but a negative and statistically insignificant relationship exists between CO_2 emissions and long-term economic growth. (Salahuddin & Gow, , 2014) finds no significant causality between CO2 emissions and economic growth in the Gulf Cooperation Council countries. Lv et al.'s (2019) findings do not support the argument that reducing CO2 emissions and/or fossil fuel consumption leads to a slowdown in economic growth in China. On the contrary, some studies have shown a long-run relationship between fossil fuel usage, GDP, and CO2 emissions, as seen in Chindo (2014), Gershon (2024), and Ghoshray and Lorusso (2025), among others. Generally, empirical evidence shows that the relationships between these variables could be uni-directional, bi-directional causality, or no causality at all (Lv et al., 2019). Therefore, the relationship between fossil fuel usage, output and CO2 emissions can be complex and influenced by various factors, including urbanization, and technological advancements.

5.0 Conclusion and Recommendations

The absence of cointegration between CO2 emissions, fossil fuel usage, and output suggests that the relationships between these variables are unstable and may be influenced by other factors in the short to medium term. However, many factors can influence carbon emissions, including Nigeria's energy mix, which is dominated by thermal and hydropower, the level of industrialisation, and population size. Similarly, in the short run, a 1% increase in economic growth leads to a 0.27% increase in carbon dioxide (CO2) emissions, suggests that economic activities are, on average, generating a moderate increase in CO2 emissions for each percentage point of economic growth. This implies that current economic systems and processes are not particularly efficient in terms of emissions. The significant impact of economic growth on CO2 emissions in the short run suggests that a combination of policy and technological interventions is needed to mitigate the environmental impact. This includes transitioning to renewable energy, implementing carbon pricing mechanisms, and investing in research and development of carbon capture technologies.

Furthermore, the study recommends that researchers and policymakers focus on other approaches to understanding and addressing the underlying drivers of these relationships. Second, to prioritize policies that promote sustainable energy transition by encouraging the adoption of renewable energy, energy efficiency measures, and low-carbon technologies to reduce reliance on fossil fuels. The study highlights that Policies focused on reducing CO2 emissions might not significantly or predictably impact economic growth, and vice versa. Second, policies that promote or restrict fossil fuel consumption may not have a lasting impact on economic growth. The study recommends a holistic energy planning approach, including investment in energy infrastructure, which might be more effective in driving economic growth than solely focusing on emission reduction or fossil fuel consumption.

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