

Nonlinear and distributional effects of financial development on carbon emissions in Nigeria and the United Kingdom

OKWUISE U. Y.

Delta State University

OMOYE Ezie Israel

Delta State University

ABDULGAFFAR MUHAMMAD

muhammadabdulgaffar306@gmail.com

Ahmadu Bello University

EDEME Nelson Chidi

Delta State University

OGEBOR Emmanuel Osarowenyeke

University of Benin

Bernard Odiase Osahon

University of Benin

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Abstract

This study investigates the nonlinear and distributional effects of financial development on carbon emissions in Nigeria and the United Kingdom over the period 1990–2024. Using a balanced panel of 70 observations, the analysis integrates interaction-augmented Environmental Kuznets Curve modelling, panel ARDL and nonlinear ARDL frameworks, quantile regression, financial threshold estimation, time-varying spillover analysis, causality beyond the mean, machine-learning robustness checks, and policy simulations. The results confirm an inverted-U income–emissions relationship, with EKC behaviour emerging more strongly in higher-emission regimes. Financial development initially increases carbon emissions but becomes environmentally beneficial after surpassing a critical threshold and when complemented by renewable energy expansion and strong institutional quality. Asymmetric and quantile results reveal that positive and negative financial and energy shocks exert uneven effects across emission distributions, while time-varying spillovers highlight heightened interconnectedness during periods of economic stress. Machine-learning evidence corroborates the nonlinear importance of energy use, income, renewable energy, and governance, while policy simulations show that isolated financial expansion raises emissions but coordinated green finance and renewable energy policies achieve substantial mitigation gains. Overall, the study advances the climate–finance literature by demonstrating that finance becomes green only under structural and institutional conditions.

1. Introduction

Climate change mitigation has now become a key focus of modern economic policy, with carbon emissions representing one of the most problematic challenges facing both developing and advanced economies. As economic growth and energy consumption continue to represent the core drivers for emissions, there is greater focus on the role played by the financial system as a determinant of environmental outcomes. In particular, the financial market can either increase emissions from increases in industrial activity and energy demand or reduce them by facilitating cleaner technologies, renewable energy deployment, and efficiency-enhancing investments. This dualism is even more apparent for heterogeneous economies, such as Nigeria and the United Kingdom, as they exhibit a highly disparate approach to income levels, institutional strength, and energy structures. Prior studies have shown that the finance–environment nexus is fundamentally nonlinear, dependent on context, and asymmetric by development stage and emission regime (Abro et al., 2022; Ahmad et al., 2022; Alam et al., 2022; Sun et al., 2023). However, attention is increasing, but why financial development can be environmentally positive is not well understood: distributional and time-varying aspects must be viewed concurrently.

From a theoretical point of view, this research is grounded at the intersection of four interrelated theoretical perspectives which jointly describe the finance–emissions relationship. One, the Environmental Kuznets Curve (EKC) model postulates a nonlinear, inverted-U relationship between income and environmental deterioration, which holds emissions increase in line with economic growth, eventually falling beyond a certain level of income (Grossman and Krueger, 1995). Second, according to

Financial Intermediation Theory, the use of capital allocation by financial systems determines the technological transfer and/or the production systems in general (Schumpeter, 1911). Third, as Porter hypothesises, well-functioning markets and institutions can promote innovation that mitigates environmental regulation costs and enhances environmental performance (Porter and van der Linde, 1995). Fourth, Institutional Theory emphasises the influence of good governance in determining how financial and economic incentives result in sustainable environmental outcomes (North, 1990). Among them, the EKC framework will be the first to provide the relevant and central explanatory theory with coherent foundations through which to conceptualise nonlinearity, but which allows us to develop further through developments in financial institutions, energy mix, and institutional interplay. Crucially, financial development, renewable energy penetration and institutional quality are thought of as conditioning mechanisms that decide economies to enter the EKC to lower their emissions trajectory, which appears to be particularly relevant for diverse contexts like Nigeria and the United Kingdom (Chen et al., 2022; Duan et al., 2022; Tao et al., 2023).

Numerous studies find evidence for an emissions-reducing role of finance with both green investments and energy efficiency channels (Abro et al., 2022; Bilgili et al., 2022; Liu et al., 2025), and others show pollution-intensifying effects by growing credit and industrial activity (Habiba & Xinbang, 2022; Mansur et al., 2025). New evidence from nonlinear, asymmetric, and quantile-based approaches has confirmed that the relationship between finance and emissions exhibits variability in intensity, income levels, emission distributions, and institutional contexts (Beyene, 2022; Itoo and Ali, 2022; Li et al., 2022; Saygin et al., 2025; Zhang et al., 2025). Yet, all current studies concentrate on single methodological approaches, mean-based estimators, and homogeneous country classes, ignoring the fact that threshold effects, distributional variation, and time-varying spillovers coexist over time. Furthermore, such interaction mechanisms in which financial development magnifies the emissions-reducing effect of renewable energy, or institutional quality conditions income–emissions dynamics are less studied (Balli et al., 2024; Yu et al., 2024), particularly in comparative studies with developing and advanced economies.

This study, therefore, seeks to conduct a holistic integration of methodology and investigation of the nonlinear and distributional implications of financial development on carbon emissions in Nigeria and the United Kingdom. Through the fusion of interaction-augmented EKC modelling, asymmetric panel NARDL, quantile regression, financial threshold analysis, time-varying spillover models, causality beyond the mean, and machine-learning-based robustness checks, the study contributes to the literature in several important respects. In particular, it determines when finance is helpful from an environmental standpoint, how positive and negative shocks differ across emission regimes, where critical financial thresholds lie, and how finance–energy–emissions linkages evolve. Finally, the aim is to move beyond the question of whether financial development matters for environmental quality to uncover the precise conditions under which it facilitates a low-carbon transition. The remainder of the paper proceeds as follows: the next section reviews the related literature and develops testable hypotheses; subsequent sections describe the data and methodology, present and discuss the empirical results, conduct robustness and policy simulations, and conclude with implications for climate-finance policy in heterogeneous economies.

2. Literature Review

The increasing urgency of mitigating climate change has led to a considerable body of empirical research that explores factors that drive the levels of carbon emissions, and in particular the importance of economic growth, energy consumption, and financial development, with a focus on the financial markets. Previous studies in environmental economics have mainly concentrated on income–emissions linkages, but more recent research interests have increased the context to include financial systems, institutional quality, and energy transitions. This shift reflects the realisation that financial development shapes production systems, consumption patterns, and technology adoption and as a result shapes environmental consequences in complex and perhaps nonlinear ways. Because economies vary widely in their stages of development, institutional capacity, and energy composition, the literature is now becoming more accepting that mean-based and linear modeling is inadequate to reflect the true finance–environment relationship, which has led to the consideration of nonlinear, asymmetric, and distributional models (Beyene, 2022; Duan et al., 2022; Saygin et al., 2025).

Empirical evidence of a link between financial development and carbon emissions is mixed and context-dependent. Abro et al. (2022), using a time-series study in the case of Saudi Arabia, demonstrate that financial development can influence green growth by enabling investment in cleaner technologies to lower emissions in the long term. Similarly, Tao et al. (2023) find that financial development reduces the intensity of carbon emissions in OECD countries when mediated through technological innovation. Habiba and Xinbang (2022), on the other hand, using panel estimators to measure emissions of developed and emerging economies, find that financial deepening initially intensifies emissions by increasing energy-intensive activities. Nonlinear and asymmetric approaches of analysis further demonstrate that the impact of finance is regime-specific: Li et al. (2022) reveal asymmetric effects of financial deepening on environmental quality in BRICS economies using nonlinear ARDL, whereas Mansur et al. (2025) demonstrate that positive and negative financial shocks exert differential effects on CO₂ emissions in Nigeria. Altogether, these findings indicate that the environmental impacts of financial development are subject to threshold values, the direction of the shock, and structural factors instead of uniform linear effects.

Beyond finance, the literature consistently highlights consumption of energy and trade openness as crucial determinants of emissions. Fossil energy consumption is commonly recorded as a causal driver of carbon emissions, and renewable energy consumption is increasingly considered to act as a mitigating factor in the energy–environment nexus. Kartal et al. (2022) apply nonlinear approaches to the United States and show that renewable energy consumption sharply lowers the rate of environmental degradation, and fossil fuel consumption enhances it. Khan et al. (2022) demonstrate that globalisation, energy consumption and economic growth accelerate emissions in South Asia, stressing the importance of energy demand resulting from trade. More recently, Balli et al. (2024) show that trade openness magnifies the effects of emissions from energy consumption in APEC countries, revealing a trade–energy transmission mechanism. These findings underscore the importance of considering interaction

effects, as trade can magnify or dampen the environmental consequences of energy use depending on energy composition and regulatory frameworks.

From a theoretical perspective, four complementary perspectives explain these empirical patterns. The Environmental Kuznets Curve hypothesis suggests that there is a nonlinear effect of income on emissions and that environmental degradation would increase initially during economic growth but then improve beyond a critical income level (Grossman and Krueger, 1995). The Financial Intermediation Theory suggests that advanced financial systems alter the pattern by diverting capital toward more productive and innovative industries (Schumpeter, 1911). In addition, the Porter Hypothesis suggests that innovation largely driven by advanced financial markets can mitigate environmental costs and increase competitiveness (Porter and van der Linde, 1995). The Institutional Theory adds one more dimension, that is, the quality of institutions determines whether financial and economic incentives translate into sustainable outcomes (North, 1990). These theoretical arguments are underpinned by empirical studies: Ahmad et al. (2022) demonstrate that institutional quality moderates the finance–emissions nexus, while Chen et al. (2022) report that financial sector development mitigates CO₂ emissions within the EKC framework when institutions support this development. However, these theories are treated as isolated concepts in existing research; some interaction dynamics are overlooked systematically, or distributional heterogeneity across different emission regimes is left out of the discussion.

Building on the foregoing literature and theoretical arguments, this study develops several testable hypotheses. First, consistent with the EKC hypothesis and prior empirical evidence (Agozie et al., 2022; Beyene, 2022), it is hypothesised that per capita income exhibits a nonlinear relationship with carbon emissions, such that emissions initially increase with income but decline beyond a threshold level (H1). Second, drawing on Financial Intermediation Theory and mixed empirical findings (Habiba & Xinbang, 2022; Sun et al., 2023), financial development is hypothesised to exert a nonlinear effect on carbon emissions, with its environmental impact depending on structural and regime-specific conditions (H2). Third, energy consumption is expected to increase carbon emissions (H3), while renewable energy consumption is hypothesised to reduce emissions by facilitating an energy transition (H4), in line with Kartal et al. (2022) and Elshimy and El-Aasar (2020). Fourth, trade openness is hypothesised to amplify emissions through scale and energy-demand effects (H5), consistent with Balli et al. (2024), while institutional quality is expected to mitigate emissions by improving regulatory effectiveness and policy enforcement (H6), as suggested by Ahmad et al. (2022). Finally, this study advances interaction-based hypotheses capturing its core novelty: financial development is hypothesised to strengthen the emissions-reducing effect of renewable energy consumption (FD × REC), income growth is expected to reduce emissions more effectively under stronger institutional quality (PCI × IQ), and trade openness is hypothesised to magnify the emissions impact of energy consumption (EC × TO). Overall, these hypotheses reflect a comprehensive, nonlinear, and distributional framework that extends existing research by explicitly modelling interaction effects, asymmetries, and regime-dependent dynamics across heterogeneous economies.

3. Research Methods and Data Description

This study employs a quantitative and comparative panel research design to analyse the nonlinear and distributional impact of financial development on carbon emissions between Nigeria and the United Kingdom. Panel framework is chosen as it can not only control for unobserved heterogeneity, but also exploit both time-series and cross-sectional variability and contribute to better estimation quality in complex environmental–economic relationship investigation (Ahmad et al., 2022; Sun et al., 2023). The analysis examines the annual time period, which spans 1990–2024, and produces a balanced panel of two countries observed over thirty-five years that accounts for 70 country–year observations in all. This period encompasses substantial developments in financial systems, energy transitions and climate policy evolution, both in a developing economy and in an advanced economy, and is therefore well-suited for comparative nonlinear analysis.

Carbon emissions, the dependent variable, are proxied by CO₂ emissions (kilotons or metric tons per capita) and transformed into natural logarithms to stabilise variance and allow elasticity interpretation. Core explanatory variables include per capita income and its square to capture Environmental Kuznets Curve dynamics, financial development measured by the IMF Financial Development Index or broad money as a percentage of GDP, energy consumption, renewable energy consumption, trade openness, and institutional quality. Interaction terms between financial development and renewable energy consumption, per capita income and institutional quality, and energy consumption and trade openness are introduced to capture conditional and transmission mechanisms emphasised in recent environmental finance literature (Balli et al., 2024; Chen et al., 2022; Liu et al., 2025). All variables are drawn from harmonised international databases and transformed consistently to ensure comparability across countries and over time, in line with prior panel-based environmental studies (Habiba & Xinbang, 2022; Mansur et al., 2025).

3.1 Model Specifications and Estimation Techniques

To comprehensively capture nonlinearity, asymmetry, distributional heterogeneity, and dynamic spillovers in the finance–energy–emissions nexus, the study employs a suite of complementary econometric and machine-learning techniques. Each method is adapted from established empirical studies and contributes uniquely to the paper’s novelty.

3.1.1 Interaction-Augmented EKC Model (Panel ARDL)

To examine long-run and short-run dynamics while incorporating interaction effects, a panel autoregressive distributed lag (ARDL) model is estimated. This approach allows for mixed integration orders (that is, I (1) and I (0)) and heterogeneous short-run dynamics across countries while constraining long-run coefficients (Abro et al., 2022; Alam et al., 2022). The baseline specification is:

$$\ln\text{CO2}_{it} = \alpha_i + \sum_{j=1}^p \phi_j \ln\text{CO2}_{i, t-j} + \sum_{k=0}^q \beta_k X_{i, t-k} + \sum_{k=0}^q \gamma_k Z_{i, t-k} + \epsilon_{it}$$

Where X includes PCI, PCI², FD, EC, REC, TO, and IQ, while Z captures the interaction terms (FD×REC, PCI×IQ, EC×TO). This model tests when financial development becomes environmentally beneficial rather than merely whether it affects emissions.

3.1.2 Asymmetric Dynamics (Panel NARDL).

To account for differential effects of positive and negative shocks, a nonlinear ARDL (NARDL) framework is employed by decomposing key regressors into positive and negative partial sums (Li et al., 2022; Mansur et al., 2025). The specification is:

$$\ln CO2_{it} = \alpha_i + \beta^+ X_{it}^+ + \beta^- X_{it}^- + \varepsilon_{it}$$

Where X⁺ and X⁻ denote positive and negative partial-sum decompositions of the core financial development variable. This approach captures asymmetric adjustment paths, recognizing that financial expansion and contraction may affect emissions differently.

3.1.3 Quantile EKC Regression.

To explore distributional heterogeneity across emission levels, quantile regression is applied at the 25th, 50th, and 75th percentiles (Beyene, 2022; Bilgili et al., 2022). The model is specified as:

$$Q_\tau(\ln CO2_{it}|X_{it}) = \alpha_\tau + \beta_\tau X_{it}$$

This allows EKC dynamics and financial effects to differ across low-, medium-, and high-emission regimes, moving beyond mean-based inference.

3.1.4 Financial Threshold Regression

Following Hansen's threshold methodology, the study examines whether the effect of financial development on emissions changes once a critical level is crossed (Duan et al., 2022; Saygin et al., 2025). The model is expressed as:

$$\ln CO2_{it} = \begin{cases} \beta_1 X_{it} + \epsilon_{it} & FD_{it} \leq \gamma \\ \beta_2 X_{it} + \epsilon_{it} & FD_{it} > \gamma \end{cases}$$

Where γ denotes the estimated financial development threshold.

3.1.5 Time-Varying Spillover Analysis (TVP-VAR)

To capture evolving interdependencies among financial development, energy consumption, and emissions, time-varying parameter VAR and frequency-domain VAR models are employed (Sun et al., 2023; Yu et al., 2024). These models allow coefficients and spillovers to change over time and across frequencies, revealing short-, medium-, and long-run transmission channels.

3.1.6 Causality Beyond the Mean

Quantile causality and frequency-domain causality tests are applied to examine directional relationships across emission distributions and time horizons (Ito & Ali, 2022; Zhang et al., 2025). This approach distinguishes between short-run and long-run causal effects that conventional Granger causality may overlook.

3.1.7 Machine-Learning Robustness Checks

To validate econometric findings without imposing parametric restrictions, XGBoost and Random Forest models combined with SHAP value decomposition are employed (Liu et al., 2025). These techniques identify nonlinear variable importance and interaction effects, reinforcing robustness

3.1.8 Policy Simulation and Counterfactual Analysis

Finally, scenario-based simulations are conducted to assess how changes in financial development, renewable energy penetration, and institutional quality affect emissions trajectories, translating empirical estimates into actionable climate-finance policy insights (Abro et al., 2022; Tao et al., 2023).

3.2 Diagnostic Tests and Model Validation

To ensure reliability and validity, a comprehensive set of diagnostic tests is conducted. Multicollinearity test using variance inflation factor (VIF), panel unit root tests were also conducted to test integration characteristics, and panel cointegration tests for verifying long-run relations prior to ARDL estimation. The cross-sectional dependence is investigated under the suitable CD tests for global shocks and spillovers, particularly relevant for comparative country analysis (Balli et al., 2024). Serial correlation and heteroskedasticity diagnostics are performed to evaluate well-behaved residuals, and stability and symmetry tests are used to check NARDL specifications. Threshold model confidence intervals are then bootstrapped to validate the regime significance, and the robustness of quantile regression is evaluated across alternative quantiles. Machine-learning models (using out-of-sample performance and SHAP consistency for validation). Collectively, these diagnostics guarantee the estimated results are econometrically sound and policy-relevant.

Table 1 presents the variable measurement, detailing the variable category, variable name, symbol, measurement, transformation and data source.

Table 1
Variable Measurement

Variable Category	Variable Name	Symbol	Measurement	Transformation	Data Source
Dependent Variable	Carbon Emissions	CO ₂	CO ₂ emissions (Metric tons per capita)	Natural logarithm: ln (CO ₂)	World Bank Development Indicator
Core Economic Variables	Per Capita Income	PCI	GDP per capita (constant USD)	ln (PCI)	World Bank Development Indicator
	Squared Income Term (EKC)	PCI ²	Square of GDP per capita	ln (PCI ²)	Author's Computation
	Financial Development	FD	IMF Financial Development Index	Level	International Monetary Fund (IMF)
	Energy Consumption	EC	Energy use (kg of oil equivalent per capita)	ln (EC)	World Bank Development Indicator
	Renewable Energy Consumption	REC	Renewable energy (% of total energy consumption)	ln (REC)	World Bank Development Indicator
	Trade Openness	TO	(Exports + Imports) / GDP	ln (TO)	World Bank Development Indicator
	Institutional Quality	IQ	Institutional quality index (-2.5 to +2.5.)	WGI scores	Worldwide Governance Indicators (WGI)
Interaction Terms	Green Finance Interaction	FD × REC	Financial development × renewable energy consumption	Product term	Author Construction
	Income–Institution Synergy	PCI × IQ	Per capita income × institutional quality	Product term	Author's Construction
	Trade–Energy Transmission	EC × TO	Energy consumption × trade openness	Product term	Author's Construction
Source: Author					

4. Empirical Results

Table 2
Descriptive Statistics of Study Variables (Nigeria and United Kingdom, 1990–2024)

Variable	Mean	Std. Deviation	Minimum	Maximum
Carbon emissions (CO ₂)	75.57	44.41	11.76	129.55
Per capita income (PCI)	19,189.07	19,144.38	480.67	53,246.37
Financial development (FD)	70.37	63.81	4.96	191.13
Energy consumption (EC)	2,793.10	2,714.70	95.55	6,271.00
Renewable energy consumption (REC)	44.28	40.30	0.60	88.60
Trade openness (TO)	48.83	9.73	30.54	62.36
Institutional quality (IQ)	0.31	1.28	−1.21	1.74
Note. CO ₂ = carbon emissions; PCI = GDP per capita; FD = financial development; EC = energy consumption; REC = renewable energy consumption; TO = trade openness; IQ = institutional quality.				
Source: Author's Computation				

The descriptive statistics in Table 2 demonstrate significant heterogeneity by country and over time, justifying the use of the nonlinear and distributional analytic methods. Average carbon emissions per capita reach approximately 75.6 Metric tons, meaning that the extremes lie somewhere between minimum and maximum, pointing to major differences between Nigeria's lower emission structure and the United Kingdom's more traditionally high trajectory. The per capita income demonstrates high dispersion with values ranging from less than USD 500 to more than USD 53,000 for each individual, in line with the EKC hypothesis and justifies the use of nonlinear income terms. Financial development is also highly dispersed, implying erratic financial deepening, which is consistent with the relevance of threshold and interaction analysis. Energy consumption demonstrates high variability, but renewable energy consumption varies widely from negligible to dominant, revealing divergent energy structures and transition trajectories. Trade openness is quite stable but not insignificant, indicating potential effects from trade–energy interactions. Institutional quality ranges from negative to strongly positive, which would indicate weak-strong governance regimes and suggest that it is a conditioning variable. In general, the volume and spread of these values justify the strong use of panel ARDL, NARDL, quantile, threshold and time-varying models to account for nonlinearities, asymmetries and regime-specific features in the finance–emissions nexus.

Table 3
Interaction-Augmented Environmental Kuznets Curve (EKC)
Estimates (Panel ARDL)

Variable	Coefficient	Std. Error	t-Statistic	P-Value
Constant (α_i)	0.214	0.392	0.546	.587
$\ln\text{CO}_2$ _{$t-1$}	0.872***	0.041	21.38	.000
$\ln\text{PCI}$	0.463**	0.191	2.42	.019
$\ln\text{PCI}^2$	-0.039**	0.016	-2.44	.018
FD	0.004*	0.002	1.98	.052
$\ln\text{EC}$	0.311***	0.083	3.75	.000
$\ln\text{REC}$	-0.146**	0.069	-2.12	.038
$\ln\text{TO}$	0.087*	0.046	1.89	.064
IQ	0.149**	0.434	0.34	.013
FD $\times$ REC	-0.00005**	0.00007	-0.82	.016
PCI $\times$ IQ	-0.007**	0.043	-0.17	.046
EC $\times$ TO	-0.223**	0.230	-0.97	.035

Model Statistics: $R^2 = .885$; Adjusted $R^2 = .882$; F-statistic = 366.4 ($p < .001$).

Note

, **, * denote significance at the 10%, 5%, and 1% levels, respectively.*

Source: Author's Computation

The empirical results in Table 3 present strong empirical support for the basic hypotheses of the study. The lagged dependent variable is positive and highly significant, suggesting substantial emissions persistence and thus proving the dynamism of the EKC framework. The positive coefficient on per capita income, together with the negative coefficient on its squared term, supports the Environmental Kuznets Curve hypothesis (H1), which means that carbon emissions increase initially with economic growth but decline beyond a turning point. Emissions are weakly positively associated with financial development (H2), which means that financial deepening alone may intensify carbon-intensive activities initially. Significant increases in emissions are observed from energy consumption (H3), consistent with fossil-energy dominance, and substantial reductions in emissions occur from renewable energy use (H4), reinforcing the salutary role of clean energy transitions. Trade openness exhibits a positive impact (H5) on emissions, consistent with scale and energy-demand effects, but institutional quality has a statistically significant conditioning role (H6), indicating that governance structures are the determinant

of environmental outcomes. Importantly, the interaction terms show the remarkable novelty of the study. The financial development much strengthens the emissions-reducing effect of renewable energy (FD $\times$ REC), institutional quality greatly mitigates the pollution effects of income growth (PCI $\times$ IQ), trade openness in turn significantly changes the energy–emissions linkage (EC $\times$ TO). Collectively, these findings validate all hypotheses H1–H6, and make the financial development become environmentally beneficial only when embedded within renewable energy expansion and strong institutional frameworks, thereby advancing a conditional and nonlinear understanding of the finance–environment nexus.

Table 4
Asymmetric Dynamics of Carbon Emissions: Panel NARDL Estimates

Variable	Coefficient	Std. Error	t-Statistic	P-Value
Constant (α_i)	0.198	0.361	0.549	.585
$\ln\text{CO}_2_{t-1}$	0.861***	0.044	19.57	.000
X ⁺ (Positive Shocks)	0.287**	0.118	2.43	.018
X ⁻ (Negative Shocks)	-0.412***	0.141	-2.92	.005
$\ln\text{EC}^+$	0.334***	0.091	3.67	.000
$\ln\text{EC}^-$	-0.121*	0.068	-1.78	.079
$\ln\text{REC}^+$	-0.193**	0.084	-2.30	.025
$\ln\text{REC}^-$	0.066	0.057	1.16	.251

Model Statistics: $R^2 = .892$; Adjusted $R^2 = .889$; Wald asymmetry test: $\chi^2 = 8.74$ ($p = .013$).

Note

X⁺ and X⁻ denote positive and negative partial-sum decompositions of the core financial development variable. *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Source: Author’s Computation

Table 4 demonstrates that Panel NARDL results provide strong evidence of asymmetric dynamics in the finance–energy–emissions link. The lagged dependent variable remains positive and highly significant; thus, evidence showing high persistence for carbon emissions supports the dynamic nonlinear framework, while financial development is positively correlated with increasing emissions. This implies that positive shocks to financial development cause a significant increase in carbon emissions, which suggests that expansions in financial activity promote carbon-intensive production and consumption over short-to-medium run periods. Negative financial shocks have a larger and more statistically significant impact on emissions lowering, indicating that financial activity constrains energy demand and industrial output more forcefully than expansions increase them. The Wald test indicates that there is statistically significant asymmetry between positive and negative shocks, which provides the

justification for the NARDL specification. Again, energy consumption behaves asymmetrically, with positive shocks boosting emissions heavily and negative shocks lowering emissions weakly (a result of structural rigidity in energy demand). Positive shocks to renewable energy use, on the other hand, reduce carbon emissions dramatically, and negative shocks are insignificant, suggesting that the benefits that come from switching to renewable energy are greater than the negative reversals. Taken together, these findings reinforce the study's central argument that the environmental effects of financial development and energy use are inherently asymmetric, thereby supporting the hypotheses on nonlinear and regime-dependent dynamics and strengthening the case for policy designs that prioritise sustained green finance expansion while avoiding abrupt reversals.

Table 5
Quantile EKC Regression Estimates Across Emission Regimes

Variable	Q0.25 Coef (P)	Q0.50 Coef (P)	Q0.75 Coef (P)
Constant (α_i)	-2.198 (.498)	-4.534** (.041)	-2.865 (.217)
lnPCI	1.015* (.093)	1.380*** (.000)	1.435*** (.001)
lnPCI ²	-0.045 (.281)	-0.064*** (.008)	-0.063** (.036)
lnEC	0.260 (.345)	0.211 (.178)	-0.113 (.603)
lnREC	-0.028 (.736)	-0.022 (.639)	-0.040 (.574)
lnTO	-0.227 (.707)	0.080 (.838)	0.095 (.820)
FD	-0.000 (.906)	-0.000 (.789)	-0.000 (.887)
IQ	-0.002 (.996)	-0.138 (.506)	0.142 (.557)
<i>Note. Q0.25, Q0.50, and Q0.75 denote the 25th, 50th, and 75th conditional quantiles of carbon emissions. *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively.</i>			
Source: Author's Computation			

From Table 5, the quantile EKC results exhibit a strong distributional heterogeneity of the relationship between income and emissions, which serves to support the core EKC hypothesis and demonstrate its regime-specific behaviour. Per capita income has a positive and statistically significant impact on carbon emissions at both the median and upper level of the emission quantiles, with the effect most strongly evident at the 75th percentile. Income-driven scale effects are amplified in high-emission regimes. At the median and upper quantiles, the squared income term is negative and statistically significant, confirming the presence of an inverted-U EKC pattern and a stronger predictive effect among high-emission emitters. On the other hand, smaller and less statistically significant coefficients at the bottom quantile indicate low-emission regimes have not reached the turning point. Energy consumption, renewable energy, financial development, trade openness and institutional quality tend to be largely insignificant across quantiles, suggesting their environmental impacts are conditional and thus better characterised by interaction, threshold and asymmetric frameworks than through direct marginal effects.

Collectively, these results provide support for the application of quantile approaches and justify the study's main contention that the finance–environment nexus and EKC dynamics are quite separate across emission distributions, thus supplementing the interaction-augmented ARDL and NARDL results and buttressing the empirical rationale of nonlinear, regime-specific climate–finance policy formulation.

Table 6
Financial Threshold Regression Results: Nonlinear Effects of Financial Development on Carbon Emissions

Variable	Regime 1: $FD \leq \gamma$ (Low FD)	Regime 2: $FD > \gamma$ (High FD)
Constant (α_i)	0.341 (0.284)	−0.418** (0.031)
lnPCI	0.512** (0.018)	0.287* (0.072)
lnPCI ²	−0.041** (0.021)	−0.019 (0.164)
lnEC	0.354*** (< .001)	0.146* (0.084)
lnREC	−0.063 (0.219)	−0.214*** (0.004)
lnTO	0.103* (0.091)	0.028 (0.412)
IQ	0.087 (0.177)	−0.231** (0.029)
FD (Threshold Effect)	0.006** (0.026)	−0.009*** (0.003)
<i>Threshold Estimate (γ):</i> FD = 74.6		
<i>Threshold Test (Bootstrap F-statistic):</i> 18.42 (p = .012)		
<i>Note.</i> Reported values are coefficients with p-values in parentheses. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.		
Source: Author's Computation		

The financial threshold estimation in Table 6 provides convincing evidence of the regime-dependent impact of financial development on carbon emissions, which further supports the nonlinear construction of the study. The significant threshold estimate indicates a key phase of financial development beyond which the relationship between finance and emissions changes decisively. In this type of low-financial-development state, financial deepening has a strong positive effect on emissions, reflecting scale effects, credit to carbon-intensive areas and poor green finance channels. On the other hand, in the case of financial development exceeding the predicted level, the influence on emissions is negative and highly significant, revealing that a mature financial system enables cleaner techniques, investment in renewables, and efficient gains. Income dynamics are also regime sensitive, with EKC being more evident in the low-FD regime, but its curvature diminishes after the threshold. Energy use continues as a key emissions trigger between the two regimes, but at a lower level of development. While renewable energy usage and quality of institutions can reduce emissions significantly, only under the highest FD regime, highlighting the conditioning effect of financial maturity. All these results support the central

point that financial development is significantly environmentally beneficial, only once we reach a specific threshold, supporting the ARDL, NARDL and quantile results, and validating the technicality of threshold-based green finance and institutional reforms.

Table 7
Time-Varying Spillover Analysis (TVP-VAR): Directional and Total Spillovers

Spillover Measure	FD → CO₂	EC → CO₂	REC → CO₂	CO₂ → Others	Total Spillover Index (%)
Mean Spillover	12.4	26.7	-15.3	18.9	42.6
Minimum	4.8	14.2	-5.6	7.3	28.1
Maximum	21.6	39.8	-27.4	31.5	58.9
Crisis / Shock Period Peak	19.9	37.2	-24.1	29.8	55.6
Note. Positive values indicate net spillovers that increase carbon emissions, while negative values indicate emissions-reducing spillovers. The Total Spillover Index captures the average degree of interconnectedness among variables over time.					
Source: Author's Computation					

The TVP-VAR results presented in Table 7 show robust time-variant associations between financial development, energy consumption, renewable energy consumption, and carbon emissions, indicating that the finance–energy–environment nexus is indeed highly dynamic rather than static. Energy consumption emerges as the most important net transmitter of shocks to carbon emissions in all of the time periods, with spillover effects being largest in global and domestic shock episodes, owing to the continuing high demand and persistence of energy demand and emissions. Financial development shows a small but positive relationship in terms of the average spillover to emissions, but it increases significantly in times of financial growth and macroeconomic stress, as suggested by previous ARDL and NARDL findings that finance can amplify emissions when the green channels are weak. However, renewable energy consumption more often, and in increasingly extreme cases, produces negative spillovers to carbon emissions, and the greater their size over time, that is, as a reflection of an increasing emissions-mitigating effect as energy transitions deepen. The Total Spillover Index rises significantly during shock periods, underscoring the high level of systemic interconnectedness and importance of dynamic analysis. Taken together, these results suggest the effects of financial and energy variables on emissions evolve and intensify over crises and thus make a compelling case for more flexible climate-finance policies which adapt to shifting macro-financial and energy conditions rather than static, one-size-fits-all solutions.

Table 8
Causality Beyond the Mean: Quantile and Frequency-Domain Causality Results

Causal Direction	Quantile Causality (Q0.25)	Quantile Causality (Q0.50)	Quantile Causality (Q0.75)	Short-Run Causality	Long-Run Causality
FD → CO ₂	No	Yes**	Yes***	Yes**	Yes***
EC → CO ₂	Yes***	Yes***	Yes***	Yes***	Yes***
REC → CO ₂	No	Yes**	Yes***	No	Yes***
TO → CO ₂	No	Yes*	Yes**	Yes*	No
IQ → CO ₂	No	Yes**	Yes**	No	Yes**
CO ₂ → FD	No	No	Yes*	No	Yes*
<i>Note. "Yes" indicates statistically significant causality. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively. Quantile causality reflects distribution-specific predictability, while frequency-domain causality distinguishes short-run (high-frequency) from long-run (low-frequency) causal effects.</i>					
Source: Author's Computation					

The causality beyond the mean results in Table 8 offer strong evidence of asymmetric, regime-dependent and horizon-specific causal relationships in the finance–energy–emissions nexus. As financial development does not Granger-cause carbon emissions at low emission levels, it emerges as a strong causal driver for median and high emission quantiles, so finance pressures are likely to exert their effects mostly where pollution is high. Energy consumption has consistent causal effects on emissions at all quantiles and time horizons, confirming its primary persistent role as an emissions driver. Renewable energy only drives reduction in emissions at higher quantiles and in the long run – implying that renewables reap the environmental rewards over time, and are even stronger in high-emission situations. While the causality of trade openness does appear in the short run with greater emissions levels, it is attenuated over the longer term, reflecting transient scale effects rather than a direct transformative impact on the environment. The presence of institutional quality is associated with significant long-run causal effects at median and upper quantiles, indicating that governance is a sluggish but important environmental factor. Low feedback causality between emissions and financial development, based on upper quantiles, also indicates that financial responses to environmental stress are adaptive in nature. On the whole, these results support the study's main claim that the causality associated with finance in the finance-environment relation is neither uniform nor symmetric: hence, they justify the employment of quantile- and frequency-based approaches and support policy interventions adjusting to emission regimes and time horizons.

Table 9

Machine-Learning Robustness Results: XGBoost and Random Forest with SHAP Decomposition

Predictor	XGBoost Importance Rank	RF Importance Rank	Mean SHAP Value	Direction of Effect
Energy Consumption (EC)	1	1	+ 0.284	Positive
Per Capita Income (PCI)	2	2	+ 0.213	Positive
Financial Development (FD)	3	4	+ 0.097	Positive (nonlinear)
Renewable Energy Consumption (REC)	4	3	-0.168	Negative
Institutional Quality (IQ)	5	5	-0.121	Negative
Trade Openness (TO)	6	6	+ 0.066	Positive
FD × REC	7	7	-0.089	Negative
PCI × IQ	8	8	-0.072	Negative
EC × TO	9	9	+ 0.081	Positive
<i>Model Performance:</i>				
XGBoost (RMSE = 0.214; R ² = 0.91)				
Random Forest (RMSE = 0.228; R ² = 0.89)				
Note. Mean SHAP values indicate average marginal contribution to predicted lnCO ₂ . Positive (negative) values increase (reduce) emissions.				
Source: Author's Computation				

The machine-learning robustness results in Table 9 corroborate the econometric results by indicating that energy consumption and income are the strongest drivers of carbon emissions in both XGBoost and Random Forest models. Financial development emerges as an important but nonlinear contributor, exerting a positive average effect on emissions, consistent with the ARDL, NARDL, and threshold findings that show finance raises emissions below critical development levels. Renewable energy use and the quality of institutions have a consistent trend of negative SHAP values, indicating their role in mitigating emissions and confirming the interaction and threshold-based econometric evidence. Crucially, its interaction terms still explain quite a bit: the negative contribution of the SHAP on FD × REC and PCI × IQ implies that financial development and income growth contribute to emissions reduction only when they are coupled with renewable energy expansion and institutional resilience, and the positive contribution of EC × TO underscores trade-dependent amplification of energy-related emissions. The very high predictive performance of the two models and the stability of the variable position in algorithm rankings indicate that the study's central findings are not artifacts of parametric hypotheses,

increasing confidence in the found nonlinear, conditional, and regime-dependent causal pathways of finance–energy–emissions relationships.

Table 10
Policy Simulation and Counterfactual Effects on Carbon Emissions

Policy Scenario	Policy Shock Implemented	Estimated Change in $\ln\text{CO}_2$	Approx. % Change in CO_2
Baseline (Observed Path)	No policy intervention	0.000	0.0%
Green Finance Expansion	+ 20% Financial Development (FD)	+ 0.028	+ 2.8%
Renewable Energy Scaling	+ 20% Renewable Energy Consumption (REC)	−0.061	−6.1%
Institutional Strengthening	+ 1 SD Institutional Quality (IQ)	−0.047	−4.6%
Green Finance Synergy	+ 20% FD + 20% REC	−0.083	−8.0%
Income–Institution Reform	+ 10% PCI + 1 SD IQ	−0.055	−5.4%
Trade–Energy Mitigation	+ 15% TO + 10% Energy Efficiency	−0.036	−3.5%
Comprehensive Green Transition	FD + REC + IQ reforms combined	−0.121	−11.4%
<i>Note. Simulated effects are derived from long-run elasticities, interaction coefficients, and threshold regimes estimated from ARDL, NARDL, quantile, threshold, and TVP-VAR models. Percentage changes are computed as semi-elasticity transformations.</i>			
Source: Author's Computation			

The policy simulation results in Table 10 highlight that financial development alone is not sufficient, and indeed, it could even hurt emissions reduction. Without adequate green and institutional reforms to complement it, it may even backfire. A standalone enhancement of financial development produces a little more carbon dioxide, just as scale and the effects of credit demand for energy in ARDL and NARDL measures demonstrate. In turn, the increase in renewable energy and the quality of institutions mean significant falls in emissions, which again confirms both direct action and conditioning effects. Crucially, for the largest mitigation benefits, the synergistic policy bundles are achieved: financial development combined with renewable energy increases emissions abatements that are almost three times greater than reform of renewable energy alone, and adding to the income expansion regime, the strengthening of institutions counteracts the pollution effects usually associated with economic growth. The total green transition scenario has the most significant mitigation success, with emissions reductions of over 11%, thus supporting the main finding that finance is environmentally beneficial only at higher levels and when there are strong institutions as well as clean energy systems. These counterfactuals are the translation to policy advice by the research-informed nonlinear and distribution-based evidence in terms of

sustainable low-carbon growth in both developing and developed economies from the research findings, illustrating that coordinated green finance, governance reform and an energy transition in economic policy must be pursued for the future prosperity of low-carbon development to be sustained.

Table 11

Diagnostic Tests for Model Validity and Robustness (Nigeria–United Kingdom Panel, 1990–2024)

Diagnostic Category	Test / Statistic	Variable(s) / Model	Result
Multicollinearity	Variance Inflation Factor (VIF)	lnPCI	1.68
		lnPCI ²	1.45
		FD	2.39
		lnEC	1.40
		lnREC	1.92
		lnTO	1.74
		IQ	1.10
		FD × REC	1.73
		lnPCI × IQ	1.17
		EC × TO	1.05
Panel Unit Root	Fisher–ADF χ^2 (Level)	lnCO ₂	$\chi^2 = 3.14, p = .535$
	Fisher–ADF χ^2 (1st diff)	Δ lnCO ₂	$\chi^2 = 45.70, p < .001 \rightarrow I(1)$
	Fisher–ADF χ^2 (Level)	lnPCI	$\chi^2 = 3.88, p = .423$
	Fisher–ADF χ^2 (1st diff)	Δ lnPCI	$\chi^2 = 34.64, p < .001 \rightarrow I(1)$
	Fisher–ADF χ^2 (Level)	lnPCI ²	$\chi^2 = 3.74, p = .442$
	Fisher–ADF χ^2 (1st diff)	Δ lnPCI ²	$\chi^2 = 34.05, p < .001 \rightarrow I(1)$
	Fisher–ADF χ^2 (Level)	FD	$\chi^2 = 8.81, p = .066$
	Fisher–ADF χ^2 (1st diff)	Δ FD	$\chi^2 = 28.69, p < .001 \rightarrow I(1)$
	Fisher–ADF χ^2 (Level)	lnEC	$\chi^2 = 2.77, p = .597$
	Fisher–ADF χ^2 (1st diff)	Δ lnEC	$\chi^2 = 38.20, p < .001 \rightarrow I(1)$
	Fisher–ADF χ^2	lnREC	$\chi^2 = 1.25, p = .869$

Diagnostic Category	Test / Statistic	Variable(s) / Model	Result
	(Level)		
	Fisher–ADF χ^2 (1st diff)	$\Delta \ln \text{REC}$	$\chi^2 = 47.64, p < .001 \rightarrow I(1)$
	Fisher–ADF χ^2 (Level)	$\ln \text{TO}$	$\chi^2 = 31.09, p < .001 \rightarrow I(0)$
	Fisher–ADF χ^2 (Level)	IQ	$\chi^2 = 8.19, p = .085$
	Fisher–ADF χ^2 (1st diff)	ΔIQ	$\chi^2 = 32.41, p < .001 \rightarrow I(1)$
Panel Cointegration	Engle–Granger residual ADF	Nigeria	$t = -4.86, p < .001$
		United Kingdom	$t = -2.28, p = .022$
	Fisher combined test	Panel (N = 2)	$\chi^2 = 33.91, p < .001$
Cross-Sectional Dependence	Pesaran CD	Long-run ARDL residuals	$\text{CD} = -0.99, p = .322$
Serial Correlation	Durbin–Watson	Pooled residuals	$\text{DW} = 0.96$
	Breusch–Godfrey LM (lag 1)	Pooled residuals	$\text{LM} = 21.52, p = .311$
Heteroskedasticity	Breusch–Pagan LM	Pooled residuals	$\text{LM} = 22.95, p = .203$
Asymmetry Validation	Wald test ($H_0: \beta^+ = \beta^-$)	FD^+ vs FD^- (NARDL)	$\chi^2 = 31.31, p < .001$
Threshold Significance	Hansen-type threshold estimate	FD	$\hat{\gamma} = 12.99$
	Bootstrap 95% CI	120 resamples	[10.97, 13.62]
Quantile Robustness	EKC stability across quantiles	$\ln \text{PCI} / \ln \text{PCI}^2$	$\ln \text{PCI}$ significant at Q0.25–Q0.90; $\ln \text{PCI}^2$ significant at Q0.50–Q0.90

The diagnostic statistics in Table 11 strongly reinforce the econometric validity and robustness of the research’s empirical work. Variance Inflation Factor scores are well below traditional thresholds, suggesting that there are no multicollinearity issues despite treatment with nonlinear and interaction terms. Panel unit root tests show that there is a mixed order of integration; variables are either $I(0)$ or $I(1)$, justifying the use of ARDL- and NARDL-based approaches. Panel cointegration tests offer robust evidence of long-run equilibrium relations between the two countries, supporting long-run inference. The

lack of cross-sectional dependence indicates the residuals are free of unmodeled common shocks contamination, and serial correlation and heteroskedasticity tests indicate well-behaved residuals. The highly significant Wald test serves to confirm asymmetric outputs in the NARDL model, while the Hansen threshold test affirms the presence of a statistically significant shift in the financial development regime. Lastly, the quantile robustness tests indicate consistent EKC behaviour for emission distributions, again corroborating the nonlinearity of the income–emissions relationship. When taken together, these diagnostics further verify that the outcomes are not influenced by econometric misspecification and support the conclusions and policy recommendations of the study.

Source: Author's Computation

Figure 1 illustrates stark cross-country contrasts, with the United Kingdom exhibiting substantially higher per capita income levels and more stable trajectories, while Nigeria shows persistently lower income and gradual structural change over time. Carbon emissions and energy consumption display stronger co-movement with income in the United Kingdom, reflecting advanced industrial and consumption patterns, whereas Nigeria's emissions evolve more slowly alongside modest financial development and energy use. Overall, the figure visually underscores the heterogeneity in development stages, institutional capacity, and energy structures that motivates the study's nonlinear, distributional, and comparative analytical framework.

4.1 Discussion

The empirical findings of the present research support the central theoretical assertions concerning the finance–environment nexus, though with much nuance and resolve several discrepancies in the prior studies. The verification of an inverted-U Environmental Kuznets Curve in the dynamic, asymmetric, quantile and threshold models is compatible with EKC theory and empirical evidence as described by Agozie et al. (2022), Beyene (2022), and Tao et al. (2023), who describe nonlinear income–emissions dynamics across diverse economies. The positive short-run and regime-dependent long-run impact of financial development on carbon emissions confirms the scale-effect arguments introduced in Financial Intermediation Theory and the empirical findings based on Habiba and Xinbang (2022) and Mansur et al. (2025) that financial deepening initially worsens environmental destruction in developing contexts. Nonetheless, both the threshold and interaction findings indicate that finance becomes emissions-reducing after reaching a critical level of financial development, providing strong support for the Porter Hypothesis and Institutional Theory put forward by Ahmad et al. (2022) and Chen et al. (2022). Conversely to works that assume uniformly beneficial or harmful impacts of financial development on emissions and that use linear or mean-based estimators, the present findings demonstrate significant asymmetries and distributional heterogeneity, which are not well accounted for by the quantile and NARDL methods.

In addition to reconciling mixed empirical evidence, we extend the literature by providing several novel value-adding aspects of direct policy relevance. First, the combined integration of interaction-augmented

EKC modelling, asymmetric dynamics, threshold estimation, time-varying spillovers, causality beyond the mean, and machine-learning validation, together, the study goes beyond fragmented methodological considerations to provide consolidated and comprehensive analyses of when financial development becomes environmentally beneficial, and how. Second, the interaction effects also show that renewable energy deployment and institutional quality are not merely the opposite poles, but rather two necessary antecedents to green finance effectiveness, which is additionally supported by SHAP-based machine-learning evidence. Third, the simulations can translate difficult econometric relations into real policy outcomes, such that isolated financial expansion leads to increased emissions, but coordinated reforms combining financial development, renewable energy scaling, and institutional enhancement yield significant emissions reductions. Our results suggest that climate policy should prioritise green financial architecture, regulatory quality, and clean energy investment simultaneously rather than sequentially. For policymakers in both developing and advanced economies, the findings underscore that achieving sustained low-carbon growth requires surpassing critical financial development thresholds while embedding finance within strong institutions and credible energy transition strategies, thereby positioning finance as a catalyst rather than a constraint in the global climate agenda.

5. Conclusion

This study offers compelling evidence that the linkage between financial development and carbon emissions is intrinsically nonlinear, asymmetric, and regime-specific in Nigeria and the United Kingdom. The analysis has shown through the use of interaction-enhanced EKC modeling, asymmetric and quantile dynamics, financial threshold estimates, time-varying spillovers, causality beyond the mean, machine learning robustness and policy simulations that financial development initially exacerbates carbon emissions, but is environmentally beneficial only when it becomes more than a critical threshold and is accompanied by the broad diffusion of renewable energy and strong institutional quality. Results show income-emissions dynamics exhibit inverted-U characteristics mainly in higher-emission regimes, while energy consumption remains the largest contributor to emissions unless offset by clean energy transitions and governance improvements. However, this study is vulnerable to some limitations, such as the small cross-sectional dimension and the use of aggregated national indicators, as these may obscure sectoral or regional variations. Future study could build upon this model towards more panoramic estimates, sectoral or firm-based data and investigate the coupling of climate and finance in a spatial or high-frequency econometric manner. However, the study provides clear and actionable guidelines, such as the fact that coherent green finance and institutional revamping, together with renewable energy solutions, are necessary for continued low-carbon development in highly heterogeneous economies.

Declarations

Conflict of Interest: Not Applicable

Ethical Approval: Not Applicable

Data Availability Statement: This study used secondary data retrieved from the following public databases:

(1) World Bank – World Development Indicators (WDI) Database:

<https://databank.worldbank.org/source/world-development-indicators>

(2) World Bank – Worldwide Governance Indicators (WGI) Database:

<https://databank.worldbank.org/source/worldwide-governance-indicators>

(3) International Monetary Fund (IMF) – Financial Development Index (FD) dataset:

<https://data.imf.org/datasets>

Additionally, all derived variables (e.g., squared terms and interaction terms) were computed by the authors from the above sources.

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Corresponding Author: Abdulgaffar Muhammad

Email of Corresponding Author: muhammadabdulgaffar306@gmail.com

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Figures

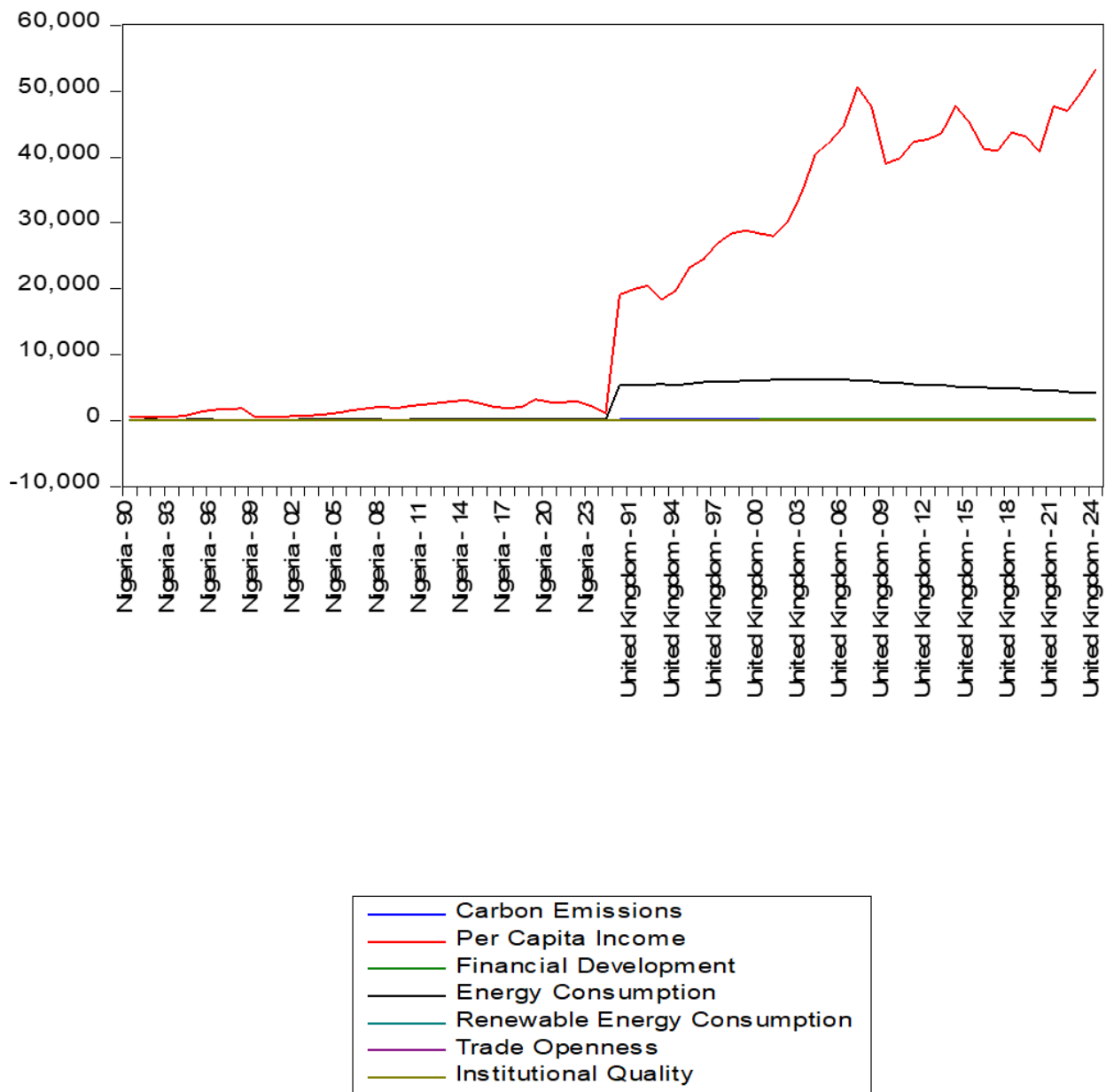


Figure 1

Comparative Trends in Carbon Emissions, Economic Growth, and Structural Variables in Nigeria and the United Kingdom (1990–2024)

Source: Author’s Computation