The Nexus between Energy Consumption and Carbon Emissions in Developing Countries and Policy Implications for Vietnam

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Abstract
Climate change has emerged as a major constraint on sustainable development in developing economies, increasing the need to identify the princpal drivers of carbon emission within the Sustainable Development Goals (SDGs) framework. This study investigates the effects of energy consumption on CO_2 emissions in 104 developing countries over 2000–2022 within the STIRPAT framework, incorporating digital technological adoption and key macroeconomic covariates. The empirical analysis employs panel data estimators, including pooled OLS, Fixed Effects model (FEM), and Random Effects model (REM), with model selection based on the Hausman test, and addresses endogeneity using an Instrumental Variables (IV) approach via Two-Stage Least Squares (2SLS). The results indicate that non-renewable energy consumption intensifies carbon emission, while renewable energy consumption has a statistically significant emissions reducing effect. Notably, digital technological adoption exhibits a nonlinear U-shaped relationship with emissions, suggesting stage-dependent effects. Economic growth, trade openness, and energy intensity are found to exacerbate emissions, while foreign direct investment (FDI) is statistically insignificant. These findings underscore the importance of accelerating the energy transition, enhancing energy efficiency, and steering digitalization toward sustainable outcomes, particularly in the context of Vietnam.

Keywords: Energy consumption, CO_2 emissions, renewable energy, non-renewable energy, developing countries.

1. Introduction

In the context of developing economies, the relationship between energy consumption and CO_2 emissions has increasingly become a pivotal issue, as rapid industrialization and urbanization have significantly boosted demand for fossil fuels, leading to substantial contributions to global emissions [1]. CO_2 emissions from human activities cause severe climate change with profound impacts such as global warming and extreme weather disasters [2]. Previous studies have indicated that CO_2 is strongly influenced by economic growth under the EKC hypothesis in the early stages of development [3], industrialization and urbanization [4], FDI which brings technology but increases emissions if uncontrolled [5], as well as technological innovation that supports CO_2 reduction through energy efficiency [6]. Energy consumption is both a major determinant of CO_2 emissions and a fundamental input into economic growth and urbanization in developing countries [7-8]. Specifically, non-renewable energy from coal, oil, and natural gas has been confirmed to have a distinctly positive impact on CO_2 emission levels through combustion processes [3], whereas renewable energy from wind, solar, and hydropower contributes to emission reductions and long-term green growth orientation [9-10]. The long-term relationship among these factors also depends on institutional quality and policy coordination, underscoring the need for updated empirical evidence to support sustainable energy transitions in developing countries [11].

Although prior studies have made important contributions to elucidating the relationship between energy consumption and CO_2 emissions, the empirical evidence remains hampered by serious substantive limitations when applied to heterogeneous developing economies. The literature has predominantly focused on testing the Environmental Kuznets Curve (EKC) hypothesis linking economic growth to CO_2 emissions [3], [12] or analyzing the impacts of FDI and urbanization [13], [14]. However, these studies have yet to fully explore the pivotal role of energy consumption structure, particularly the distinction between non-renewable and renewable sources, in shaping CO_2 emission levels across diverse regional contexts [9], [15]. This research gap has become especially pressing amid recent global economic shocks: the 2008 financial crisis, which curtailed fossil fuel demand and triggered structural economic adjustments [16]; the COVID-19 pandemic, which induced a record CO_2 emissions decline in 2020 [17]; and ongoing geopolitical conflicts, which continue to disrupt regional energy architectures [18].

This study contriutes to the literature by examining how the composition of energy consumption influence CO_2 emission across developing economies. First, by disaggregating energy consumption into renewable and non-renewable components, the study uncovers their heterogeneous impacts on emission dynamics, addressing the limitation of prior studies that rely on aggregate energy measures [9], [15]. Second, a regional analysis is conducted to capture cross-country heterogeneity in energy dependence and emission patterns, thereby providing nuanced policy insights across different regions [16], [17]. Third, the empirical strategy employs panel data econometric techniques, including pooled Ordinary Least Squares (OLS), the Fixed Effects (FE) model, and the Random Effects (RE) model, with model selection based on the Hausman and Breusch–Pagan LM tests, and further addresses potential endogeneity using an Instrumental Variables (IV) approach implemented through Two-Stage Least Squares (2SLS). The findings provide important policy implications for developing countries, particularly Vietnam in its pursuit of net-zero emissions by 2050, by supporting strategies that promote renewable energy adoption, enhance energy efficiency, and mitigate environmental degradation.

Vietnam provides a particularly context for examining these relationships. As a rapidly industrializing and urbanizing developing economy, is facing continuously increasing energy demand alongside growing pressure to reduce carbon emissions [18]. The manufacturing and processing sectors serve as the main drivers of economic growth in Vietnam [19]. These sectors lead to rapidly increasing electricity demand, particularly in industry forecasted to surge by 2030 [20]. At the same time, Vietnam exhibits a strong dependence on fossil fuels, particularly coal as the dominant component of its power mix [21]. This heavy reliance on coal-based power generation has contributed significantly to rising CO_2 emissions in recent years, highlighting the critical importance of examining the energy consumption structure when designing climate-mitigation policies. Vietnam also faces the dual challenge of maintaining high economic growth while fulfilling its net-zero emissions commitment by 2050 [22], [23], which makes empirical evidence from developing countries that explicitly account for renewable versus non-renewable energy use highly relevant for policy formulation in the Vietnamese context.

The study aims to analyze the relationship between energy consumption and CO_2 emissions in developing countries over the period 2000–2022, while also considering regional differences and the disaggregation of energy sources, thereby proposing policy implications for Vietnam toward sustainable development.

2. Conceptual framework

The relationship between energy consumption and CO_2 emissions has been extensively documented in environmental economics, particularly in developing and emerging economies. Empirical evidence consistently shows that non-renewable energy consumption significantly elevates greenhouse gas emissions. Specifically, [24] demonstrate that industrial production and energy use drive pollution in major emitting countries, while [25] identify oil dependency as the primary factor increasing emissions. In contrast, renewable energy expansion reduces emissions and enhances environmental quality [26], while [27], [28] highlight synergies with private sector growth and mitigation benefits alongside energy efficiency improvements. These findings highlight the importance of energy-mix transformation for emissions mitigation and sustainable development.

In addition, empirical studies indicate that CO_2 emissions are not solely driven by energy consumption but are also significantly influenced by a range of macroeconomic factors [29], [30]. Urbanization and energy intensity further exacerbate environmental pressure by increasing large-scale energy consumption, with energy intensity identified as one of the most consistent and significant determinants of CO_2 emissions. In addition, foreign direct investment (FDI) exhibits a dual effect, as it may increase emissions through scale expansion while simultaneously contributing to emission reduction via the diffusion of cleaner technologies [31], [32]. Furthermore, trade openness and technological innovation are recognized as important channels for improving environmental performance through efficiency gains and technology transfer, although the impact of innovation tends to be nonlinear [24], [33].

This study is grounded in well-established theories in environmental economics. The STIRPAT model [34], as a stochastic extension of the IPAT framework [35], provides a flexible empirical approach for quantifying the impacts of population, affluence, and technology on environmental outcomes. Moreover, the concept of sustainable development, as articulated in the Brundtland Report [36], underscores the need to balance economic growth with environmental sustainability, a principle further operationalized in the United Nations (2015) Sustainable Development Goals, particularly through the promotion of clean and renewable energy systems. The Environmental Kuznets Curve (EKC) hypothesis [37] provides a theoretical basis for a potential inverted U-shaped relationship between economic growth and environmental degradation. Finally, the Pollution Haven and Pollution Halo hypotheses [38], [39] provide competing theoretical perspectives to explain the environmental effects of foreign direct investment. The integration of these theories provides a comprehensive analytical that underpins the empirical investigation of this study (Figure 1)

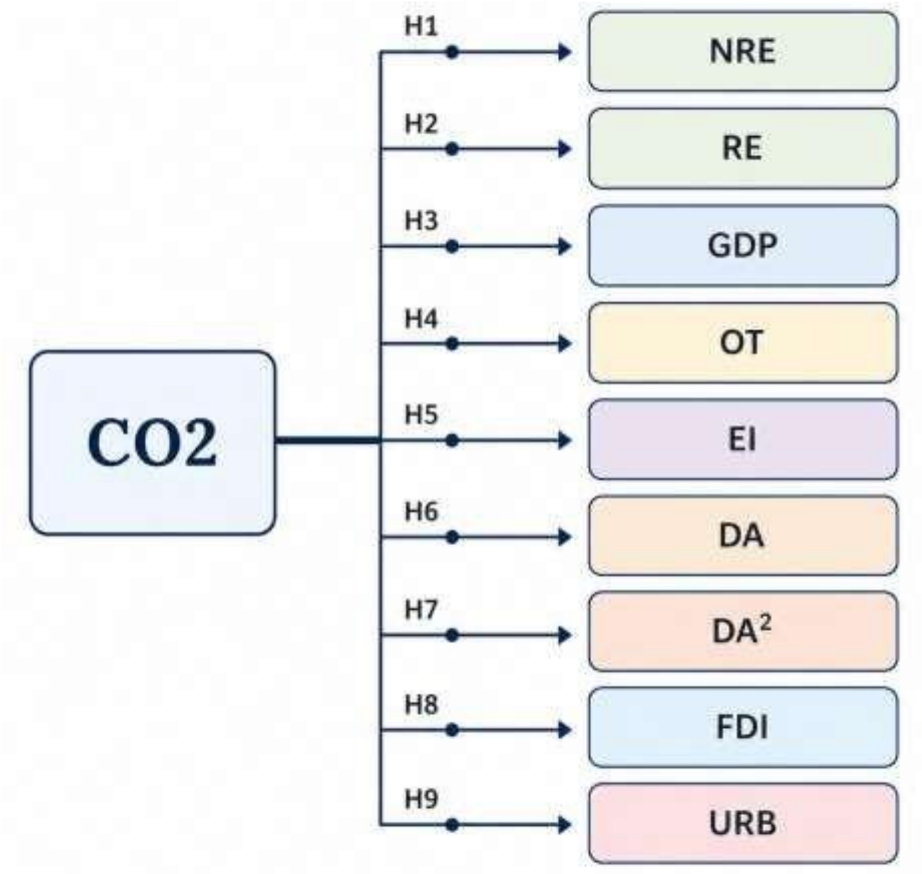

Figure 1: Proposed Research Model *(Source: Authors)*

Based on the proposed research model, the following hypotheses are developed:
H1: Non-renewable energy consumption has a positive impact on CO_2 emissions.: Non-renewable energy consumption, particularly fossil fuels, is considered a primary source of CO_2 emissions due to its high carbon intensity and widespread use in production and consumption activities. In developing countries, where fossil fuels continue to dominate the energy structure, rising energy demand further intensifies CO_2 emissions. [29] show that non-renewable energy consumption is positively associated with CO_2 emissions, especially in emerging and middle-income economies. Similarly, [10] confirm that this relationship persists in both the short and long run. In addition, [40] also find that non-renewable energy consumption generates a persistent positive shock on CO_2 emissions, highlighting its strong environmental impact. Therefore, non-renewable energy consumption is expected to exert a positive effect on CO_2 emissions.
H2: Renewable energy consumption has a negative impact on CO_2 emissions: The use of renewable energy contributes to reducing dependence on fossil fuels, thereby limiting emissions and improving environmental quality. [40] show that renewable energy plays a crucial role in mitigating CO_2 emissions by replacing conventional fossil fuel sources. Similarly, [26] further confirm this effect in the context of developing economies. In addition, [27] also find that greater renewable energy consumption significantly reduces CO_2 emissions in developing countries. Accordingly, revewable energy consumption is hypothesized to reduce CO_2 emission.
H3: Economic growth has a positive impact on CO_2 emissions: In the early stages of development, economic growth is often accompanied by increased energy consumption and production expansion, which in turn leads to higher CO_2 emissions. This is consistent with the arguments of [41] within the Environmental Kuznets Curve (EKC) framework and is empirically supported by [29] for the middle-income countries. In addition, [42] also find that economic growth is positively associated with CO_2 emissions, particularly in developing economies with high energy demand and industrial expansion. Therefore, economic growth is expected to exert a positive effect on CO_2 emissions.
H4: Trade openness has a positive impact on CO_2 emissions: Trade openness is considered a key driver of production and goods exchange, particularly in developing economies, thereby increasing energy demand and CO_2 emissions. According to [41], within the EKC framework, economic openness is often associated with higher fossil fuel consumption. Similarly, [29] find that trade tends to increase emissions in middle-income countries. In addition, [43] also show that trade openness is positively linked to CO_2 emissions, particularly in developing countries where pollution-intensive industries are concentrated. Therefore, trade openness is expected to exert a positive effect on CO_2 emissions.
H5: Energy intensity has a positive impact on CO_2 emissions: Energy intensity reflects the efficiency of energy use within an economy; higher energy intensity implies greater energy consumption per unit of GDP, thereby leading to increased CO_2 emissions. [44] argues that energy intensity is a direct driver of rising emissions in developing countries. This view is further supported by empirical evidence from [28], who find that energy intensity has a statistically significant positive impact on CO_2 emissions, alongside long-run relationships among energy consumption, economic growth, and environmental degradation.

H6: Digital technological adoption has a positive impact on CO_2 emissions: Technological innovation can improve energy efficiency and promote cleaner production processes, thereby contributing to emission reduction. However, in developing and resource-dependent economies, technological progress in the early stage is often associated with production expansion and industrialization, causing the scale effect to outweigh the energy-saving effect and leading to higher CO_2 emissions [45]. However, at higher levels of technological development, innovation tends to promote cleaner and energy-efficient technologies, which helps reduce emissions through the technique effect [46], [47]. Accordingly, the relationship between technological innovation and CO_2 emissions is expected to be nonlinear (**H7**).

H8: Foreign direct investment has a negative impact on CO_2 emissions: FDI can serve as a channel for technology transfer and improved production efficiency, thereby contributing to the reduction of CO_2 emissions. [48] finds that FDI enhances technology and reduces emission intensity, while [31] show that capital inflows from developed countries tend to reduce CO_2 emissions due to higher environmental standards. In addition, [49] also indicate that FDI promotes renewable energy consumption and supports cleaner production processes in developing Asian economies. FDI is therefore hypothesized to reduce CO_2 emissions through technology-transfer and efficiency channels.

H9: Urbanization has a positive impact on CO_2 emissions: Urbanization increases energy demand for transportation, construction, and consumption, thereby leading to higher CO_2 emissions. [50] finds that urbanization has a strong positive effect on emissions in emerging economies, while [51] confirms this relationship in the context of Vietnam. In addition, [52] also show that rapid urban expansion significantly increases CO_2 emissions, particularly during the early stages of urban development. Therefore, urbanization is expected to exert a positive effect on CO_2 emissions.

3. Method

This study employs a panel data regression framework to examine the determinants of total CO_2 emissions across 104 countries over the period 2000–2022. The dataset is constructed using secondary data obtained from the World Development Indicators (WDI) and the International Energy Agency (IEA), accessed via the World Bank DataBank, which provide consistent and internationally comparable indicators on environmental, economic, and energy-related variables. The sample is defined according to the World Bank FY2026 income classification (updated on July 1, 2025), based on 2024 GNI per capita (Atlas method), including only developing countries classified as low-income (≤ USD 1,135), lower-middle-income (USD 1,136–4,495), and upper-middle-income (USD 4,496–13,935), while high-income economies (> USD 13,935) are excluded, in order to ensure consistency with the research objectives and enhance cross-country comparability. To maintain a robust and reliable dataset, the initial list of countries was refined by excluding those with significant missing data, ensuring that all variables remain consistently defined across both temporal and cross-sectional dimensions. By utilizing this panel data approach, the study effectively controls for unobserved country-specific heterogeneity while capturing dynamic trends, leading to more efficient estimations and robust statistical inferences regarding the environmental–economic nexus [53].

The empirical framework is rooted in the theoretical foundations of environmental economics, which explain the key drivers of carbon emissions, particularly the STIRPAT framework [34], [54] and the Environmental Kuznets Curve hypothesis proposed by [41]. These frameworks emphasize that CO_2 emissions are jointly determined by economic scale, energy structure, and technological progress. A substantial body of empirical evidence consistently indicates that energy consumption, especially non renewable energy, acts as a primary driver of increasing emissions [24], [30], [55], whereas renewable energy contributes to environmental improvement through the substitution of fossil fuels [26], [40]. In addition, socioeconomic factors such as urbanization, digital technology adoption, and foreign direct investment also affect environmental outcomes through both direct and indirect channels, reflecting the role of structural transformation and technological advancement in shaping the relationship between economic growth and emissions [31], [33], [48-50], [56], [57]. Building upon the analytical framework proposed in [66] and subsequently extended in [50], this study develops a baseline model to examine the determinants of CO_2 emissions, specified as follows:

$$CO_{2_{it}} = f(Energy_{it},\ GDP_{it},\ OT_{it},\ URB_{it}, EI_{it}) \qquad (1)$$

Consistent with the STIRPAT approach, the model is specified in a multiplicative form to capture elasticities:

$$CO_2 = A.\, Energy_{it}^{\beta1}.\, GDP_{it}^{\beta2}.\, OT_{it}^{\beta3}.\, URB_{it}^{\beta4}.\ EI_{it}^{\beta5} \qquad (2)$$

To better reflect the heterogeneity of energy sources, total energy consumption is disaggregated into non-renewable energy (NRE) and renewable energy (RE). Furthermore, digital technological adoption (DA) and foreign direct investment (FDI) are incorporated into the model to capture the effects of digital transformation and international capital inflows on environmental quality. The extended model is specified as follows:

$$CO_2 = A.\, NRE_{it}^{\beta1}.\, RE_{it}^{\beta2}.\, GDP_{it}^{\beta3}.\, OT_{it}^{\beta4}.\, URB_{it}^{\beta5}.\, EI_{it}^{\beta6}.\, DA_{it}^{\beta7}.\, FDI_{it}^{\beta8} \qquad (3)$$

To capture the potential nonlinear effect of digitalization, the squared term of digital technological adoption is introduced:

$$CO_2 = A.\, NRE_{it}^{\beta1}.\, RE_{it}^{\beta2}.\, GDP_{it}^{\beta3}.\, OT_{it}^{\beta4}.\, URB_{it}^{\beta5}.\, EI_{it}^{\beta6}.\, DA_{it}^{\beta7}.\, (DA^2)_{it}^{\beta8}\ .\, FDI_{it}^{\beta9} \qquad (4)$$

Taking natural logarithms of both sides, the model is transformed into a log-linear specification suitable for empirical estimation:

$$\ln CO_{2it} = \ln A + \beta1\ \ln NRE_{it} + \beta2\ \ln RE_{it} + \beta3\ \ln GDP_{it} + \beta4\ \ln OT_{it} + \beta5\ \ln URB_{it} + \beta6\ \ln EI_{it} + \beta7\ \ln DA_{it} + \beta8\ \ln DA^2_{it} + \beta9\ \ln FDI_{it} + \epsilon_{it} \qquad (5)$$

Let β0 = lnA, after substituting in Equation (5):

$lnCO_{2it} = \beta0 + + \beta1\ lnNRE_{it} + \beta2\ lnRE_{it} + \beta3\ lnGDP_{it} + \beta4\ lnOT_{it} + \beta5\ lnURB_{it} + \beta6\ lnEI_{it} + \beta7\ lnDA_{it} + \beta8\ lnDA^2_{it} + \beta9\ lnFDI_{it} + \epsilon_{it}$ (6)

In this model, the dependent variable is CO_2 emissions. The independent variables include economic growth (GDP), non-renewable energy consumption (NRE), renewable energy consumption (RE), energy intensity (EI), urbanization (URB), trade openness (OT), digital technology adoption (DA), the squared term of digital technological adoption (DA^2) and foreign direct investment (FDI). The term ϵ represents the stochastic error, while Table 1 provides comprehensive definitions for all variables.

Table 1. Data description of variables

Variable Category	**Variable**	**Unit**	**Description**
Dependent variable	CO_2	Mt CO2e	Carbon dioxide (CO2) emissions (total) excluding LULUCF
Explained variables	NRE	% of total electricity generation	Electricity production from oil, gas and coal sources
	RE	% of total energy consumption	Renewable energy consumption
Control variables	GDP	Constant 2015 PPP US$	Gross domestic product at constant 2015 prices
	OT	% of GDP	Trade openness
	URB	% of total population	Urban population
	EI	MJ/$2021 PPP of GDP	Energy intensity level of primary energy
	DA	% of population	Individuals using the Internet
	FDI	% of GDP	Foreign direct investment, net inflows

The study initially employs conventional panel data estimation techniques, including pooled Ordinary Least Squares (OLS), the Fixed Effects Model (FEM), and the Random Effects Model (REM), to provide baseline insights into the relationships among variables. Model selection is conducted using the F-test and the Hausman specification test [58], which are used to detect the presence of individual effects and determine the appropriate specification between FEM and REM.

Given the multi-country nature of the dataset, the empirical model may be subject to common econometric issues such as multicollinearity, serial correlation, heteroskedasticity, and cross-sectional dependence, which can affect the efficiency and reliability of conventional estimators. To diagnose these issues, several standard tests are employed, including the Variance Inflation Factor (VIF) for multicollinearity, the Wooldridge test for autocorrelation in panel data, the Modified Wald test for groupwise heteroskedasticity, and the Pesaran CD test [59] for cross-sectional dependence. In addition, the study addresses potential endogeneity arising from reverse causality, omitted variable bias, or measurement errors. The Durbin–Wu–Hausman (DWH) test is applied to identify endogenous regressors. To obtain consistent estimates in the presence of endogeneity, the study employs the Instrumental Variables (IV) approach using Two-Stage Least Squares (2SLS) as the primary estimation method.

The validity of the instrumental variables is further assessed through a set of standard diagnostic tests, including the first-stage F-statistic for instrument relevance, the Hansen J test for over-identifying restrictions, and the Kleibergen–Paap LM and rk Wald F statistics to examine model identification and detect weak instruments. These procedures ensure the robustness and reliability of the empirical findings.

4. Results

4.1. Overview of Regional Energy Consumption and CO_2 Emissions

Table 2 reveals substantial disparities in CO_2 emission levels across regions. Asia records the highest average emissions (397.949 Mt CO_2e), reflecting significant environmental pressures associated with rapid industrialization and rising energy demand. In contrast, Oceania exhibits the lowest average emissions (0.929 Mt

CO_2e), indicating a relatively limited scale of emissions. Other regions, including Europe, South America, and Africa, display moderate average emission levels; however, considerable variation exists among countries within each region, as evidenced by the wide range between minimum and maximum values.

Table 2. Average CO_2 Emissions in Developing Countries by Region period 2000-2021 (*Unit: Mt CO_2e*)

Region	Mean	Max	Min
North America	8.596	29.668	0.049
Africa	25.691	487.925	0.090
Asia	397.949	12,551.86	0.249
Europe	83.333	392.983	3.233
Oceania	0.929	6.621	0.000
South America	50.361	193.794	3.643
Overall mean	144.032	12,551.86	0.0001

(Source: Summarized by authors)

4.2. Impact of Energy Consumption on CO_2 Emissions

The descriptive statistics reveal substantial heterogeneity across the sampled developing countries during the 2000–2022 period. CO_2 emissions exhibit considerable dispersion (SD = 2.577; range: −9.21 to 9.438), reflecting large cross-country differences in environmental performance. The average level of non-renewable energy consumption (lnNRE = 3.654) exceeds that of renewable energy consumption (lnRE = 3.158), indicating the continued dominance of fossil-fuel-based energy systems. Meanwhile, digital technology adoption and FDI display relatively high variability, suggesting uneven levels of technological development and foreign capital inflows across countries. In contrast, GDP, trade openness, energy intensity, and urbanization show lower dispersion, implying relatively more stable economic and demographic patterns within the sample. Overall, these statistics highlight significant structural differences in energy use, digital development, and economic conditions, which may contribute to divergent CO_2 emission patterns among developing economies (Table 3).

Table 3. Descriptive Statistics of variables

Variable	Obs	Mean	Std. Dev.	Min	Max
$lnCO_2$	1990	2.246	2.577	-9.21	9.438
lnNRE	1990	3.654	1.362	0	4.615
lnRE	1990	3.158	1.417	-2.303	4.588
lnGDP	1990	23.852	1.997	18.702	30.416
lnOT	1990	4.216	0.451	3.057	5.851
lnEI	1990	1.599	0.501	0.322	3.242
lnDA	1990	2.29	1.599	-4.468	4.572
$lnDA^2$	1990	7.798	6.096	0	20.905
lnFDI	1990	1.241	0.706	-0.12	2.508
lnURB	1990	3.817	0.429	2.477	4.523
	(Source: Authors' estimation using STATA 17)				

Table 4 shows that $lnCO_2$ is strongly and positively correlated with lnGDP (0.936), indicating that economic growth remains closely associated with higher carbon emissions in developing countries, while its negative correlation with lnRE (-0.386) supports the emission-mitigating role of renewable energy. In addition, $lnCO_2$ exhibits moderate positive correlations with lnURB (0.340) and lnDA (0.302), suggesting that urbanization and digitalization may increase energy demand and environmental pressure. By contrast, the correlations between $lnCO_2$ and lnOT (-0.194), lnEI (-0.095), and lnFDI (-0.031) are relatively weak, implying limited direct linear relationships. Furthermore, most pairwise correlations among the independent variables remain below 0.5, except for the correlation between lnDA and lnDA2 (0.863), which is expected due to the squared transformation of the same variable. Overall, these results suggest that severe multicollinearity is unlikely to be a major concern, although VIF tests are further conducted to ensure the robustness of the estimations.

Table 4. Correlation Analysis Results

Variables	$lnCO_2$	lnNRE	lnRE	lnGDP	lnOT	lnEI	lnDA	$lnDA^2$	lnFDI	lnURB
$lnCO_2$	1.000									
lnNRE	0.173	1.000								
lnRE	-0.386	-0.398	1.000							
lnGDP	0.936	0.127	-0.280	1.000						
lnOT	-0.194	0.043	-0.203	-0.303	1.000					

lnEI	-0.095	-0.219	0.029	-0.132	-0.012	1.000				
lnDA	0.302	0.143	-0.284	0.292	0.168	-0.308	1.000			
lnDA^2	0.298	0.093	-0.288	0.296	0.127	-0.288	0.863	1.000		
lnFDI	-0.031	-0.022	-0.044	-0.079	0.356	-0.032	0.086	0.036	1.000	
lnURB	0.340	0.165	-0.415	0.338	0.132	-0.194	0.470	0.442	0.064	1.000
(Source: Authors' estimation using STATA 17)										

Figure 2 provides preliminary evidence on the relationships among the study variables. CO_2 emissions appear to increase with non-renewable energy consumption and economic growth, while exhibiting an inverse association with renewable energy consumption. In addition, the scatter plots reveal a nonlinear relationship between lnDA and lnDA^2, supporting the inclusion of a quadratic digitalization term in the empirical specification. More importantly, no strong linear dependence is observed among the explanatory variables, suggesting that multicollinearity is unlikely to be a serious concern. Overall, the visual patterns are broadly consistent with theoretical expectations and support the suitability of the proposed regression model.

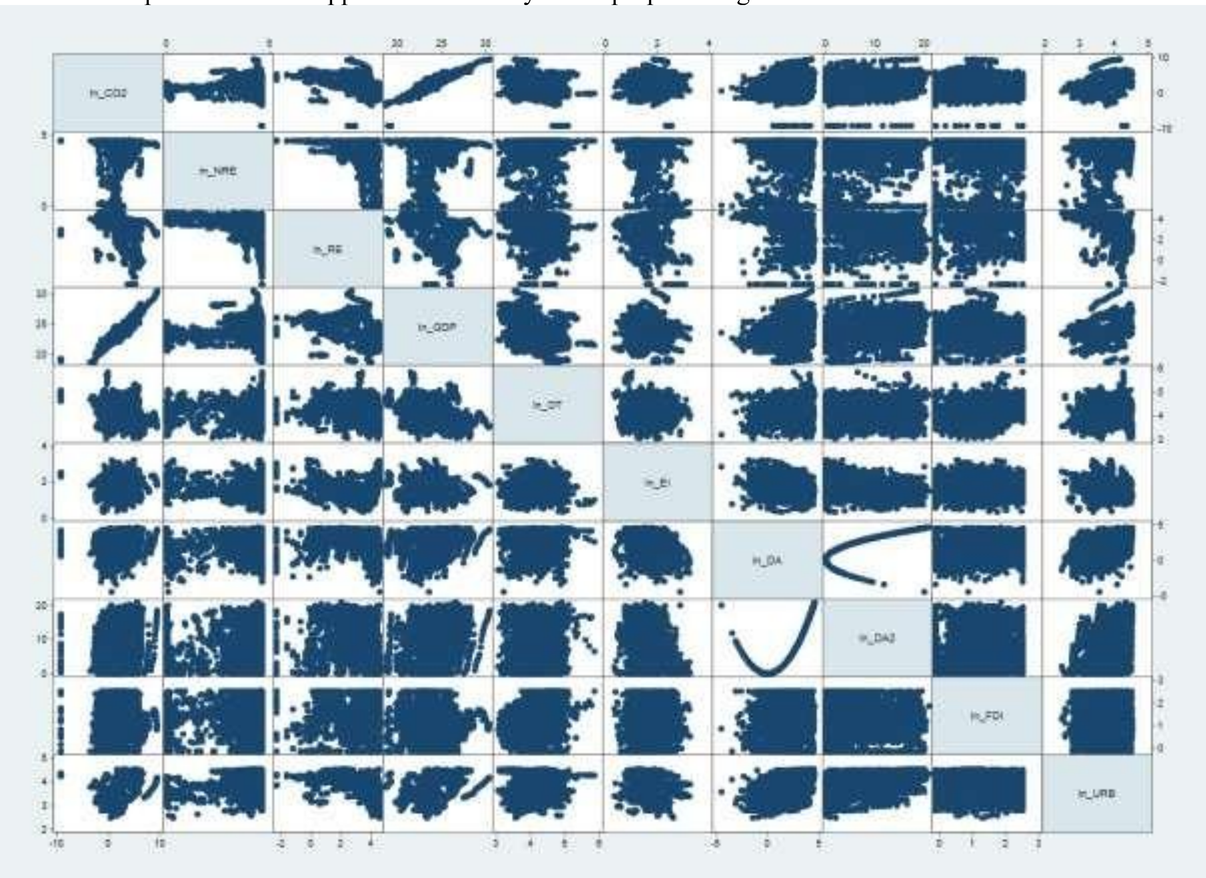

Figure 2. Scatter Plot Matrix of Variables in the Model
(Source: Authors' estimation using STATA 17)

The VIF test results in Table 5 indicate that multicollinearity is not a concern in the model. Specifically, the VIF values range from 1.151 to 1.562, with a mean value of 1.382, all well below the commonly accepted threshold. This confirms that the independent variables are not highly linearly correlated and exhibit sufficient independence. Therefore, the model is considered statistically reliable for subsequent estimations.

Table 5. Multicollinearity Test among Independent Variables

	VIF	1/VIF
lnRE	1.562	0.64
lnURB	1.515	0.66
lnDA	1.464	0.683
lnOT	1.463	0.683
lnGDP	1.462	0.684
lnNRE	1.26	0.794
lnEI	1.182	0.846
lnFDI	1.151	0.868
Mean VIF	1.382	.

(Source: Authors' estimation using STATA 17)

The study proceeds to estimate the Pooled OLS (POLS), Fixed Effects Model (FEM), and Random Effects Model (REM). The Breusch–Pagan LM test (Chi²(1) = 17,786.06; p-value = 0.0000) indicates that the Random Effects Model is preferred over pooled OLS. Subsequently, the Hausman test (Chi²(9) = 34.19; p-value = 0.0000) suggests that the Fixed Effects Model is the most appropriate specification. However, diagnostic tests reveal several econometric issues. The Modified Wald test (Chi²(104) = 81,085.24; p-value = 0.0000) confirms the presence of heteroskedasticity, while the Wooldridge test (F(1,102) = 201.285; p-value = 0.0000) indicates autocorrelation. In addition, the Pesaran cross-sectional dependence test (CD = 10.30; p-value = 0.000) rejects the null hypothesis of cross-sectional independence, implying significant cross-sectional dependence in the dataset (Table 6).

Table 6. Results of Model Selection and Diagnostic Tests

Test	Statistic	P-value
Breusch-Pagan LM	Chi²(1) = 17,786.06	0.0000
Hausman	Chi²(9) = 34.19	0.0000
Modified Wald	Chi²(104) = 81,085.24	0.0000
Wooldridge	F(1,102) = 201.285	0.0000
Pesaran CD	CD = 10.30	0.000

(Source: Authors' estimation using STATA 17)

In environmental and energy economics, several studies have suggested that renewable energy and CO_2 emissions may exhibit a bidirectional causal relationship, thereby creating potential endogeneity issues in regression models. Specifically, the expansion of renewable energy use contributes to reducing CO_2 emissions, while increasing environmental pressure and stricter climate policies may simultaneously stimulate greater investment in renewable energy. [60] using a GMM-PVAR model for 27 OECD countries, found both unidirectional and bidirectional causal relationships between renewable energy sources and CO_2 emissions. Similarly, [61] identified bidirectional causality between renewable energy consumption and CO_2 emissions in developing countries using a panel VECM framework. [62] also documented dynamic interactions between renewable energy consumption and CO_2 emissions across 172 countries based on System-GMM and PVAR estimations. In addition, [63] emphasized that dynamic GMM estimators are widely employed in energy–environment studies to address endogeneity arising from reverse causality and omitted variable bias. Therefore, this study employs the IV-2SLS estimator to mitigate the potential endogeneity of renewable energy and ensure the consistency of the estimated coefficients.

The FE-2SLS results in Table 7 indicate that renewable energy consumption significantly reduces CO_2 emissions, whereas non-renewable energy use, GDP, trade openness, energy intensity, and urbanization significantly increase environmental degradation. GDP and energy intensity exhibit the strongest positive effects, confirming that economic expansion and inefficient energy use remain key drivers of carbon emissions. Digital technology adoption demonstrates a significant inverted U-shaped relationship with CO_2 emissions, suggesting that digital development initially increases emissions but eventually contributes to environmental improvement beyond a certain threshold. In contrast, FDI remains statistically insignificant, implying that foreign direct investment does not exert a stable direct impact on environmental quality in the sampled countries. Overall, the high explanatory power of the model and the significant Wald chi-square statistic confirm the robustness and reliability of the FE-2SLS estimation.

Table 7. Estimation Results Using the FE-2SLS Model

$lnCO_2$	Coefficient	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
lnRE	-0.127	0.02	-6.25	0.000	-0.167	-0.087	***
lnNRE	0.075	0.01	7.69	0.000	0.056	0.094	***
lnGDP	0.962	0.033	29.25	0.000	0.897	1.026	***
lnOT	0.078	0.02	3.93	0.000	0.039	0.116	***
lnEI	0.516	0.03	17.05	0.000	0.457	0.575	***
lnDA	0.024	0.006	3.74	0.000	0.011	0.036	***
$lnDA^2$	-0.008	0.001	-5.76	0.000	-0.01	-0.005	***
lnFDI	0.001	0.007	0.20	0.840	-0.012	0.015	
lnURB	0.557	0.057	9.78	0.000	0.445	0.669	***
Constant	-23.837	0.796	-29.96	0.000	-25.396	-22.277	***

Mean dependent var	2.246	SD dependent var		2.577
Overall r-squared	0.879	Number of obs		1990
Chi-square	455,470.982	Prob > chi2		0.000

R-squared within	0.781	R-squared between		0.881
*** $p<0.01$, ** $p<0.05$, * $p<0.1$				

(Source: Authors' estimation using STATA 17)

Figure 3 presents the histogram of residuals obtained from the FE-2SLS estimation. The residuals are approximately centered around zero and broadly follow a bell-shaped distribution, with most observations concentrated near the mean and only a few values located in the tails. The overlaid normal density curve also indicates that the residual distribution is reasonably close to normality, suggesting the absence of severe skewness or extreme outliers. Overall, this result supports the adequacy and statistical reliability of the FE-2SLS specification, implying that the estimated coefficients and statistical inferences are unlikely to be substantially biased by abnormal residual behavior.

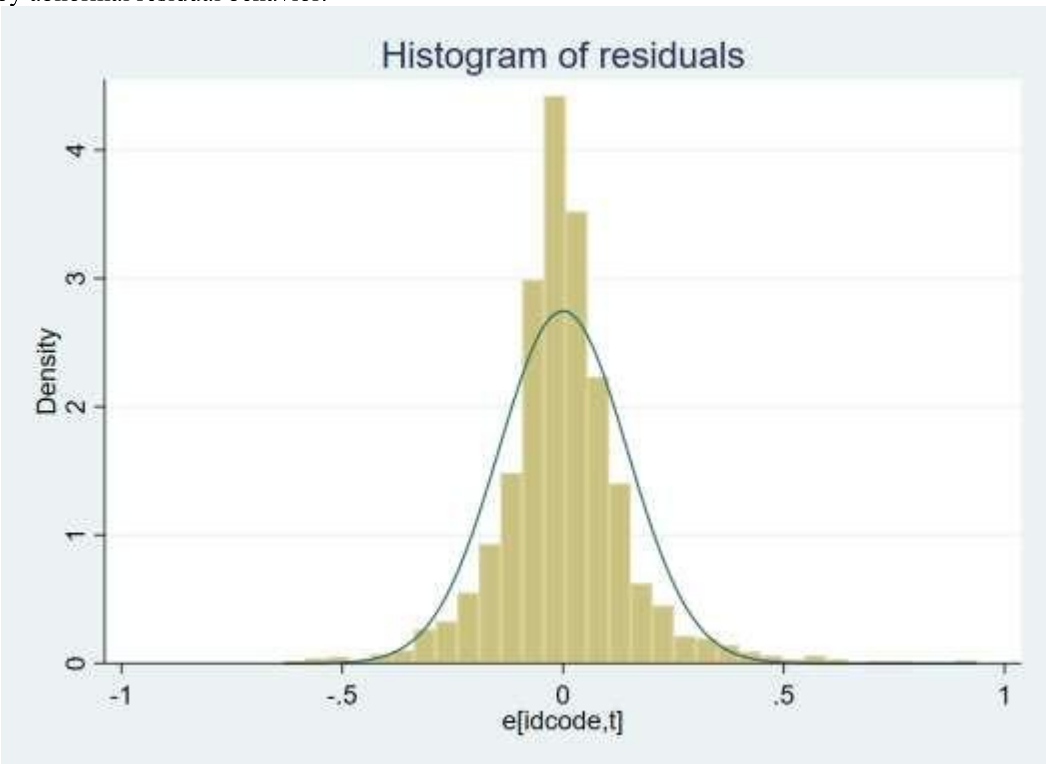

Figure 3. Distribution of Residuals
(Source: Authors' estimation using STATA 17)

The robustness analysis confirms that the main findings obtained from the FE-2SLS model remain largely unchanged across alternative estimation techniques, including RE-2SLS, FE-DK, and FGLS. The coefficients of renewable energy, non-renewable energy, economic growth, trade openness, energy intensity, and urbanization consistently retain their signs and statistical significance, supporting the reliability of the baseline estimates. Notably, the positive coefficient of DA and the negative coefficient of DA^2 are preserved across all specifications, providing strong evidence of an inverted U-shaped relationship between digitalization and CO_2 emissions. Although the linear effect of DA becomes statistically insignificant under FGLS, the negative and significant coefficient of DA^2 persists, suggesting that the nonlinear effect of digitalization is robust to alternative estimators. In contrast, FDI remains statistically insignificant in all models, with coefficients close to zero. This finding implies that the environmental impact of foreign direct investment is likely offset by the coexistence of scale effects, which tend to increase emissions, and technology spillover effects, which may enhance environmental efficiency, resulting in no discernible net effect on CO_2 emissions. Overall, the consistency of coefficient signs, magnitudes, and significance levels across estimators reinforces the robustness of the FE-2SLS results and suggests that the main conclusions are not driven by endogeneity, heteroskedasticity, or cross-sectional dependence (Table 8)

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Table 8. Summary of FE-2SLS, RE-2SLS, FE-DK, and FGLS Models

Variables		**$LnCO_2$**		
	FEM-2SLS	REM-2SLS	FE-DK	FGLS
lnRE	-0.127***	-0.125***	-0.133***	-0.180***
	(0.020)	(0.019)	(0.022)	(0.010)

lnNRE	0.075***	0.072***	0.075***	0.102***
	(0.010)	(0.010)	(0.023)	(0.008)
lnGDP	0.962***	1.029***	0.959***	1.101***
	(0.033)	(0.027)	(0.057)	(0.007)
lnOT	0.078***	0.077***	0.077***	0.025**
	(0.020)	(0.020)	(0.012)	(0.013)
lnEI	0.516***	0.540***	0.513***	0.529***
	(0.030)	(0.028)	(0.070)	(0.020)
lnDA	0.024***	0.018***	0.024*	-0.000
	(0.006)	(0.006)	(0.013)	(0.006)
$lnDA^2$	-0.008***	-0.008***	-0.008***	-0.003**
	(0.001)	(0.001)	(0.002)	(0.002)
lnFDI	0.001	0.000	0.001	0.002
	(0.007)	(0.007)	(0.011)	(0.003)
lnURB	0.557***	0.501***	0.557***	0.099***
	(0.057)	(0.055)	(0.078)	(0.033)
Constant	-23.837***	-25.248***	-29.744***	-25.019***
	(0.796)	(0.660)	(1.292)	(0.230)
Observations	1990	1990	1990	1990
R^2 F Chi-square	0.7813 . 455,470.98	0.7808 . 7,438.48	0.7813 2,343.80 .	. . 30,775.22

Standard errors in parentheses: * $p < 0.1$, $^{**}p < 0.05$, *** $p < 0.01$
(Source: Authors' estimation using STATA 17)

4. Discussions and conclusion

The findings provide evidence of systematic relationships between socio-economic factors and CO_2 emissions in developing countries. Non-renewable energy consumption, GDP growth, urbanization, and energy intensity are associated with higher emission levels. These results are consistent with the studies of [41] on the Environmental Kuznets Curve (EKC) hypothesis, as well as [10], [29], [51]. In contrast, an increase in the share of renewable energy demonstrates a significant mitigating effect on emissions, in line with the findings of [26, [40]. Furthermore, environmental effects of technological innovation appear more complex: although innovation can improve energy efficiency, in developing economies, scale and rebound effects often dominate, resulting in a net increase in CO_2 emissions [57], [64]. Additionally, the rapid expansion of digital technologies and ICT infrastructure increases electricity demand from data centers, cloud computing, and smart devices, thereby further contributing to global carbon emissions, particularly in countries with fossil fuel-dependent energy structures [65]. These empirical findings suggest that effective emissions mitigation requires both transformation of the energy mix and improvements in resource efficiency.

5. Policy Implications for Vietnam

The findings suggest that accelerating Vietnam's energy transition should remain a central priority for achieving its net-zero commitment. The empirical results show that renewable energy contributes to reducing CO_2 emissions, whereas greater reliance on non-renewable energy significantly increases environmental pressure. This implies that expanding renewable electricity generation alone is insufficient unless it is accompanied by a gradual reduction in coal dependence and continued improvements in grid infrastructure. In this regard, the effective implementation of the National Power Development Plan (PDP8) and related renewable energy policies will be essential to facilitate a more sustainable energy transition while maintaining energy security.

Another important implication concerns is to improve energy efficiency. The estimated coefficient of energy intensity indicates that inefficient energy use remains one of the major contributors to rising carbon emissions in developing economies. For Vietnam, this suggests that emission reduction policies should place greater emphasis on enhancing energy productivity across industrial production, transportation, and commercial buildings rather than relying solely on expanding energy supply. Promoting energy-efficient technologies, strengthening mandatory efficiency standards, and encouraging cleaner production practices would enable Vietnam to reduce emissions while sustaining economic growth.

Finally, the nonlinear relationship between digitalization and CO_2 emissions suggests that digital transformation does not automatically lead to environmental improvements. During the early stages of digital development, expanding digital infrastructure may increase electricity demand and consequently carbon emissions. Therefore, digital transformation policies should be integrated with clean energy development and industrial decarbonization strategies. Encouraging smart energy management systems, digital monitoring of industrial energy use, and low-carbon digital infrastructure would help ensure that digitalization becomes an effective instrument for supporting Vietnam's long-term green transition rather than creating additional environmental pressure.

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