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Hydropower and Carbon Emissions in Vietnam: Revisiting the Energy-Environment Nexus through an ARDL Analysis

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Abstract

This study investigates the dynamic relationship between carbon dioxide (CO_2) emissions, economic growth, energy consumption, and hydropower in Vietnam over the period 1990-2023 using the autoregressive distributed lag (ARDL) approach. The bounds testing results suggest a possible long-run relationship among the variables, although the evidence for cointegration remains inconclusive. The error-correction term indicates a stable, albeit gradual, adjustment toward equilibrium following short-term shocks. The empirical findings reveal that energy consumption significantly increases CO_2 emissions in the short run, highlighting Vietnam's persistent dependence on conventional energy sources. By contrast, hydropower does not exhibit a statistically significant short-run effect on emissions within the estimated model. However, neither energy consumption nor hydropower shows a statistically significant long-run impact in the ARDL framework, suggesting that deeper structural characteristics of Vietnam's energy system may dominate long-term emission trajectories. Economic growth also does not exhibit a direct, statistically robust long-run effect on carbon emissions within the linear ARDL framework, suggesting that environmental outcomes may depend more on broader structural factors, such as technological progress, the energy transition, and improvements in energy efficiency. This study contributes to the existing literature by explicitly disaggregating hydropower from aggregate energy consumption, thereby allowing for a more differentiated assessment of environmental effects across energy sources. The findings suggest that, while hydropower remains an important component of Vietnam's renewable energy strategy, its estimated environmental effects are not statistically robust in ei-

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ther the short or long-run. These results underscore the importance of broader renewable energy diversification, improved energy efficiency, and stronger institutional support for Vietnam's low-carbon transition.

Keywords

CO_2 Emissions, Energy Consumption, Hydropower, Economic Growth, ARDL Model, Vietnam

1. Introduction

Global climate change has emerged as one of the most pressing challenges to sustainable development, with carbon dioxide (CO_2) emissions widely recognized as the principal driver of global warming. According to the Intergovernmental Panel on Climate Change, the sharp increase in greenhouse gas emissions over recent decades has been driven primarily by fossil fuel-based energy production and consumption [1]. This creates substantial pressure for countries to sustain economic growth while simultaneously reducing environmental degradation and transitioning toward cleaner energy systems.

The relationship among economic growth, energy consumption, and CO_2 emissions has long attracted considerable attention in environmental and energy economics. The Environmental Kuznets Curve (EKC) hypothesis posits that environmental pollution tends to increase during the early stages of economic growth but gradually declines as income reaches a threshold due to technological advancements, structural economic changes, and increased environmental awareness [2]. However, this study uses a linear model and does not include GDP-squared; therefore, the EKC is treated as a general theoretical framework to explain the relationship between economic growth and the environment rather than being directly tested. Building on this framework, numerous empirical studies have identified energy consumption as a major determinant of carbon emissions, particularly in developing economies that depend heavily on conventional energy sources [3]. In response to rising environmental concerns, renewable energy has increasingly been recognized as a critical pathway toward decarbonization. Among renewable energy sources, hydropower occupies a particularly important position due to its relatively mature technology, large-scale generation capacity, and contribution to energy security [4]. Nevertheless, its environmental implications remain contested, as its effectiveness in reducing carbon emissions may vary across national energy systems, hydrological conditions, and infrastructure constraints.

Despite the expanding literature, most previous studies have relied on aggregate energy indicators or grouped renewable energy sources into a single composite measure, thereby overlooking the heterogeneous environmental impacts of specific energy sources. This aggregation may obscure the distinct contribution of hydropower to emission dynamics. Although studies such as Sadorsky [5] examined the broader relationship between renewable energy and economic growth, limited attention has been given to isolating the specific role of hydropower in shaping long-run environmental outcomes.

Vietnam provides a particularly relevant context for investigating this issue. As one of the fastest-growing economies in Southeast Asia, Vietnam has experienced rapid industrialization, substantial growth in electricity demand, and a marked increase in CO_2 emissions over the past three decades. At the same time, hydropower has remained a central component of the national electricity generation mix and has played an important role in supporting energy security. However, empirical evidence on whether hydropower contributes to sustained carbon mitigation in Vietnam remains limited, particularly when distinguishing between short-run and long-run effects.

This study addresses this gap by examining the dynamic relationship among CO_2 emissions, economic growth, energy consumption, and hydropower in Vietnam over the period 1990-2023 using the autoregressive distributed lag (ARDL) framework. To ensure robustness, the analysis is further validated using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS). By explicitly disaggregating hydropower from aggregate energy consumption, this study provides new evidence on the heterogeneous environmental effects of energy sources. It contributes to the growing literature on energy transition and sustainable development in emerging economies.

2. Literature Review

Recent studies show that CO_2 emissions are influenced not only by economic growth but also by production structure and investment flows. For example, a study of Nam *et al.* [6] using the ARDL model found a long-term relationship among economic growth, industrial production, foreign direct investment, and CO_2 emissions in Vietnam, underscoring the role of macroeconomic factors in explaining environmental variability. Many recent international studies continue to affirm the central role of energy consumption in driving CO_2 emissions. The study by Dogan and Inglesi-Lotz [7] showed that energy consumption from non-renewable sources increases CO_2 emissions, whereas renewable energy tends to reduce environmental pollution. Similarly, [8] noted that the relationship between economic growth and CO_2 emissions is not universal but depends on each country's energy structure and level of development, requiring a detailed consideration of each energy component rather than using a composite indicator.

In developing economies, energy consumption—especially from fossil fuels—is often linked to increased CO_2 emissions, reflecting an energy-dependent growth model [8]. However, the common approach in previous studies has been to use a composite energy variable, which can obscure the differences between energy sources.

Recently, studies have begun shifting to a disaggregated approach, separating renewable energy sources to assess each source's environmental impact more accurately. Among these, hydropower is considered a significant renewable energy source, particularly in countries with abundant water resources like Vietnam. According to the International Energy Agency, hydropower remains the largest renewable energy source globally, playing a significant role in reducing greenhouse gas emissions by replacing fossil fuels.

Recent empirical studies provide evidence that hydropower plays a positive role in reducing CO_2 emissions. For example, Balsalobre-Lorente *et al.* [9] indicated that renewable energy, including hydropower, contributes to reducing environmental pollution in both the short and long term in OECD economies. Similarly, the study by Dogan and Inglesi-Lotz [7] highlighted that renewable energy sources may weaken the relationship between economic growth and CO_2 emissions through the energy substitution effect. The study by Pao and Fu [10] showed that hydropower can help reduce CO_2 emissions by replacing fossil fuels, but the extent of the impact depends on each country's specific conditions. However, empirical evidence on hydropower is not entirely consistent. Some studies show that hydropower's impact may be evident only in the short term, while its long-term impact is not statistically significant. This is explained by factors such as limitations on development scale, dependence on hydrological conditions, and indirect environmental impacts [8]. Furthermore, in some cases, hydropower can generate environmental costs, such as ecosystem changes and methane emissions from reservoirs, further complicating the overall assessment of its environmental efficiency.

In Vietnam, studies on the relationship between energy and CO_2 emissions have primarily focused on overall energy consumption and economic growth. In contrast, the role of specific energy sources, particularly hydropower, has not been fully analyzed. This creates a significant research gap, given that Vietnam has a high proportion of hydropower in its electricity structure. The failure to separate hydropower may lead to inaccurate assessments of the environmental impact of renewable energy.

Therefore, this study adopts a decomposition approach, separating hydropower from overall energy consumption to clarify its specific role in relation to CO_2 emissions. This approach not only supplements empirical evidence for the Vietnamese case but also contributes to the international research stream by providing a more detailed perspective on the heterogeneous environmental impacts of different energy sources.

3. Data and Methodology

3.1. Data

This study utilizes annual time-series data for Vietnam from 1990 to 2023, collected from the World Development Indicators (WDI) database of the World Bank. Specifically, per capita CO_2 emissions are taken from the data code EN.GHG.CO_2.PC.CE.AR5; GDP per capita from NY.GDP.PCAP.CD; energy consumption per capita from EG.USE.PCAP.KG.OE; and the share of hydropower in electricity production from EG.ELC.HYRO.ZS. These are reliable data sources widely used in empirical studies on environmental economics and energy. No missing values were found during the study period; no interpolation or missing data processing was required. Although emissions are reported as CO_2 equivalents according to the AR5 methodology, the study still uses the term "CO_2 emissions" to ensure consistency with most previous studies.

Based on theoretical foundations and recent studies, the model includes four main variables: per capita CO_2 emissions, per capita GDP, energy consumption, and the share of hydropower in electricity production. Including both the overall energy consumption variable and the hydropower share variable in the same model aims to differentiate between the scale impact of energy demand across the entire economy and the structural impact of renewable energy sources. Given Vietnam's continued heavy reliance on fossil fuels, the energy consumption variable reflects the extent of energy demand expansion, while the hydropower variable reflects the degree of structural shift in electricity generation towards cleaner sources, consistent with recent studies emphasizing the importance of energy structure separation [7] [9].

All variables were transformed to natural logarithms to reduce variance, limit heteroskedasticity, and allow for elastic interpretation of regression coefficients. For the hydropower weight variable, a logarithmic transformation was appropriate because all values were positive during the study period; it also stabilized the data series and improved the interpretability of the estimated coefficients. However, the coefficient of the hydropower variable should be understood as the marginal impact of changes in the electricity production structure, holding overall energy consumption constant. **Table 1** provides a detailed description of the variables used in the study.

Table 1. Description of research variables.

Variables	Name	Unit	Data source	WDI code
CO_2 per capita emissions	$LNCO_2$	metric tons of CO_2 equivalent per capita (log)	WDI	$EN.GHG.CO_2.PC.CE.AR5$
GDP per capita	LNGDP	USD/person (log)	WDI	NY.GDP.PCAP.CD
Energy use	LNENERGY	kg oil equivalent/person (log)	WDI	EG.USE.PCAP.KG.OE
Hydropower (% of electricity produced)	LNHYDRO	% (log)	WDI	EG.ELC.HYRO.ZS

Source: Author's compilation.

The selection of variables in this study is based not only on theoretical foundations but also reflects the practical characteristics of the Vietnamese economy, where energy consumption remains significantly dependent on traditional sources. At the same time, hydropower plays a crucial role in the electricity production structure. This approach allows simultaneous assessment of the impacts of economic growth, energy demand, and the energy transition on CO_2 emissions in both the short- and long-term.

3.2. Methodology

Based on the theoretical framework linking economic growth, energy consumption, and environmental emissions, a research model was developed to assess the impacts of GDP, energy consumption, and hydropower on CO_2 emissions in Vietnam. When the variables are transformed into natural logarithms, the long-term equation can be expressed as a log-linear equation as follows:

$$\ln \mathrm{CO}_{2t} = \beta_0 + \beta_1 \ln \mathrm{GDP}_t + \beta_2 \ln \mathrm{ENERGY}_t + \beta_3 \ln \mathrm{HYDRO}_t + \varepsilon_t$$

In this case, the coefficients β_i reflect the long-term elasticity of CO_2 emissions with respect to the explanatory variables. However, since time series data are often non-stationary, directly estimating the above equation can lead to spurious regression. To overcome this problem and simultaneously analyze short-term and long-term dynamics, the study applies the ARDL model proposed by [11]. The optimal lag structure of the ARDL model was determined using the Akaike Information Criterion (AIC). Given the relatively small sample size, the maximum lag length was restricted to two to avoid overparameterization and preserve degrees of freedom. At the same time, this method is particularly suitable for small samples and is widely used in recent studies on energy and the environment [7]. The general form of the ARDL (p, q_1, q_2, q_3) model in the study can be rewritten as an unconstrained error correction model (UECM) as follows:

$$\begin{aligned}\Delta \ln \mathrm{CO}_{2t} &= \alpha_0 + \sum_{i=1}^{p} \alpha_i \Delta \ln \mathrm{CO}_{2t-i} + \sum_{j=0}^{q_1} \beta_j \Delta \ln \mathrm{GDP}_{t-j} + \sum_{k=0}^{q_2} \gamma_k \Delta \ln \mathrm{ENERGY}_{t-k} \\ &+ \sum_{m=0}^{q_3} \delta_m \Delta \ln \mathrm{HYDRO}_{t-m} + \lambda_1 \ln \mathrm{CO}_{2t-1} + \lambda_2 \ln \mathrm{GDP}_{t-1} \\ &+ \lambda_3 \ln \mathrm{ENERGY}_{t-1} + \lambda_4 \ln \mathrm{HYDRO}_{t-1} + u_t\end{aligned}$$

The coefficients of the first-differenced variables capture the short-run dynamics among the variables, while the lagged level variables are used to examine the existence of a long-run equilibrium relationship within the ARDL framework. However, the long-run effects are interpreted based on the normalized long-run coefficients derived from the estimated ARDL model rather than directly from the lagged level terms in the UECM specification [11]. The existence of cointegration among the variables is evaluated using the Bounds testing approach, which assumes no long-run relationship between the variables.

When a long-term relationship exists, the ARDL model can be converted to an Error Correction Model (ECM), allowing for the assessment of the system's rate of adjustment to long-term equilibrium after short-term shocks. The general form of the ECM model is represented as follows:

$$\Delta \ln \mathrm{CO}_{2t} = \sum \theta_i \Delta \mathrm{X}_{t-i} + \phi \mathrm{ECT}_{t-1} + \varepsilon_t$$

ECT_{t-1} is the correction error derived from the long-term equation, and the expected coefficient ϕ is negative and statistically significant, reflecting the rate of adjustment to equilibrium. A larger absolute value of this coefficient indicates a faster rate of adjustment, which is particularly important in assessing the long-term stability of the economic-environmental system [8].

3.3. Tests in the Study

Before estimating the ARDL model, the study conducted unit root tests to determine the degree of integration of the variables. Specifically, two common tests, the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP), were used to test for stationarity of the data series. Combining these two tests increases the reliability of the results, especially for time-series data that may be affected by autocorrelation and heteroskedasticity [12]. A necessary condition for applying the ARDL model is that the variables are only integrated at degree I(0) or I(1), and no variable is integrated at degree I (2) [11].

After determining the degree of integration, the Bounds test is performed to assess the presence of a cointegrating relationship between the variables. This test is based on the F-statistic and is compared with the critical values for the case where the variables are I(0) or I(1). If the F-statistic exceeds the upper threshold I(1), the hypothesis that there is no long-term relationship is rejected. Conversely, if the F-value is less than the lower threshold I(0), there is no evidence of cointegration; in the case between the two thresholds, the result is considered indeterminate [11]. This is one of the outstanding advantages of the ARDL method compared to traditional cointegration methods.

When confirming the existence of a long-term relationship, the Error Correction Model (ECM) is used to analyze short-term dynamics and the rate of adjustment to equilibrium. The coefficient of the correction error is expected to be negative and statistically significant, reflecting the system's ability to return to equilibrium after short-term shocks [13].

To strengthen the reliability of the ARDL model estimates, this study uses two additional stability testing methods: Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS). Combining these methods enables the assessment of the consistency of long-term cointegration among CO_2 emissions, energy consumption, economic growth, and hydropower. In time-series studies, especially with relatively small sample sizes, the use of supplementary estimation methods to confirm the stability of long-run coefficients is an important practice to minimize the risk that conclusions are influenced by the specific characteristics of each estimation technique [14] [15].

The combination of FMOLS and DOLS in this study is particularly important. While ARDL provides a clear distinction between short- and long-term effects through error-correction mechanisms, FMOLS and DOLS validate the stability of long-term cointegration coefficients using different correction strategies. If the results show consistency in the sign and statistical trend of the effect across the three methods, it will strongly reinforce the reliability of the research conclusions. This approach has been widely applied in recent studies on the relationships among energy consumption, economic growth, and carbon emissions to strengthen the persuasiveness of empirical evidence.

To ensure the model's fit, a series of diagnostic tests was performed. First, the Breusch-Godfrey test was used to detect autocorrelation in the residuals, and the Breusch-Pagan-Godfrey test was applied to test for heteroskedasticity. In addition, the Jarque-Bera test was used to assess the normality of the residuals, a crucial assumption in regression models. Furthermore, the Ramsey RESET test was performed to detect model misfits, thereby ensuring that the model was correctly specified [16].

The model's stability is tested using the CUSUM and CUSUMSQ tests, which assess the stability of the estimated coefficients over time. If the test curves fall within the confidence interval, the model is considered stable. In addition, the Granger causality test is used to determine the direction of interaction among the model's variables, thereby providing further evidence of the dynamic relationships among economic growth, energy consumption, hydropower, and CO_2 emissions [17].

4. Results and Discussions

Descriptive statistics (**Table 2**) show that the dataset, comprising 34 annual observations, fairly accurately reflects the trends in CO_2 emissions, energy consumption, hydropower production, and economic growth in Vietnam during the study period. Among these, the $LNCO_2$ variable has the largest standard deviation (0.7807), indicating significant variability in carbon emissions over the years, reflecting the impact of industrialization and changes in the energy structure. The LNENERGY variable has the highest mean (6.2555) and a relatively low standard deviation (0.4384), suggesting a fairly stable upward trend in energy demand over the long term, consistent with Vietnam's economic development and production expansion.

Table 2. Descriptive statistics of variables.

Variable	Obs.	Mean	Std. Dev.	Minimum	Maximum
$LNCO_2$	34	0.1759	0.7807	−1.1719	1.3593
LNENERGY	34	6.2555	0.4384	5.6012	6.9306
LNHYDRO	34	3.0218	0.5384	1.7875	3.9155
LNGDP	34	3.7981	0.3181	3.3294	4.3204

Source: Author's calculation results.

For hydropower (LNHYDRO), the standard deviation is 0.5384, and the range is quite wide, indicating relatively strong fluctuations in hydropower output, potentially influenced by hydrological conditions, seasonality, and reservoir system exploitation capacity. Meanwhile, LNGDP has the lowest standard deviation (0.3181), indicating a more stable economic growth trend than the energy variables. Overall, differences in the degree of variability across variables suggest that the relationship between CO_2 emissions and explanatory factors may be dynamic and evolve differently across short-run and long-run horizons, thereby confirming the suitability of the ARDL model for analyzing both short- and long-term impacts in this study.

4.1. Unit Root Tests

Before proceeding with ARDL model estimation, the study performed unit root tests to determine the integration order of the variables. Two common tests, ADF and PP, were used to ensure the consistency of the results. Table 3 presents the results of the unit root tests for the model's variables.

Table 3. Unit root test results (ADF and PP).

Variable	ADF (Level)	PP (Level)	ADF (First Diff)	PP (First Diff)	Conclusion
$LNCO_2$	-0.9697^{NS}	-1.7079^{NS}	−4.4908***	−4.4387***	I(1)
LNENERGY	-0.1705^{NS}	0.0660^{NS}	−6.4305***	−8.2135***	I(1)
LNGDP	-1.1134^{NS}	-0.9243^{NS}	−5.7630***	−7.4853***	I(1)
LNHYDRO	-0.7753^{NS}	-1.0666^{NS}	−4.6536***	−5.2114***	I(1)

***: statistically significant at the 1% level; ^{NS}: non-statistically significant; Source: Author's calculation results.

The unit root test results from both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests indicate that all variables are non-stationary at their levels but become stationary after first differencing, implying that they are integrated of order one, I(1). Although the PP test provides weak evidence of stationarity for certain specifications of the GDP variable, the overall results across model specifications and testing approaches consistently support treating LNGDP as an I(1) variable. The use of both ADF and PP tests enhances the robustness of the stationarity assessment because the PP test is more flexible in correcting for serial correlation and heteroskedasticity in the error term [12]. Since none of the variables is integrated of order two, I(2), the ARDL bounds testing approach remains appropriate for the analysis, consistent with the framework proposed Pesaran [11]. One important advantage of the ARDL methodology is its ability to accommodate variables integrated of order I(0) and I(1) within the same empirical framework.

4.2. Cointegration Testing and the Error Correction Model

After confirming that none of the variables is integrated of order two, I(2), the study proceeded to examine the existence of a long-run relationship using the ARDL Bounds testing approach. The Bounds test results indicate that the calculated F-statistic (2.886) exceeds the lower critical bound but remains below the upper bound at the conventional significance levels. Therefore, the evidence of cointegration is not conclusive based solely on the Bounds test results. However, the error-correction term estimated in the ARDL-ECM framework is negative and statistically significant, suggesting a stable long-run adjustment mechanism among CO_2 emissions, energy consumption, economic growth, and hydropower generation in Vietnam. Accordingly, the long-run relationship identified in the model should be interpreted with caution, particularly given the relatively small sample size and the borderline nature of the Bounds test results (Table 4).

Table 4. Bounds test results.

Statistics	Value	Significance Level	I(0)	I(1)
F-statistic	2.886	10%	2.72	3.77
k	3	5%	3.23	4.35
		1%	4.29	5.61

Source: Author's calculation results.

In addition, studies using the ARDL method in Vietnam also record the existence of a long-term relationship between CO_2 emissions and macroeconomic variables, thereby further strengthening the robustness of the results in this study. Given the statistically significant and negative error-correction term, the ECM results (Table 5) are interpreted as indicative of a stable adjustment mechanism, although the long-run relationship should be treated cautiously due to the inconclusive Bounds test.

Table 5. ECM model results.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	−1.169	0.339	−3.447	0.002
ΔLNGDP	−0.187	0.127	4.7741	0.000
ΔLNENERGY	0.606	0.049	−3.7903	0.000
ΔLNHYDRO	0.038	0.028	1.3657	0.184
CointEq (−1)	−0.083	0.023	−3.5962	0.001

Source: Author's calculation results.

The coefficient on the error correction term, CointEq (−1), is negative and statistically significant at the 1% level, suggesting the presence of a stable, though gradual, adjustment process toward equilibrium following short-run disturbances. Specifically, the estimated coefficient of −0.083 implies that approximately 8.3% of short-run disequilibrium is corrected in each period, indicating a relatively slow adjustment toward long-run equilibrium. In the short run, energy consumption exerts a positive and statistically significant effect on CO_2 emissions, indicating that higher aggregate energy demand directly intensifies environmental pressure in Vietnam. By contrast, hydropower's share in electricity generation does not exhibit a statistically significant short-run effect on CO_2 emissions, suggesting that its environmental contribution is not statistically robust within the estimated period. Economic growth displays a negative, statistically significant short-run coefficient, suggesting that short-term increases in GDP may be associated with temporary improvements in energy efficiency, technological progress, or structural adjustment. The results indicate that aggregate energy consumption remains the dominant short-run determinant of CO_2 emissions in Vietnam.

4.3. ARDL Estimation Results, Diagnostic Testing, and Causality Analysis

The study estimates the long-term coefficients from the ARDL model (Table 6).

Table 6. Conditional error correction regression results.

Criteria		Value		
R-squared		0.7664		
Adjusted R-squared		0.7331		
F-statistic		22.9694***		
Durbin-Watson		1.8867		
Variable	**Coeficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	−1.1690	0.7504	−1.5578	0.1319
$LNCO_2$ (−1)	−0.0832	0.0811	−1.0267	0.3144
LNGDP (−1)	0.0480	0.0493	0.9746	0.3391
LNENERGY (−1)	0.1836	0.1275	1.4396	0.1624
LNHYDRO (−1)	−0.0333	0.0282	−1.1819	0.2484
ΔLNGDP	−0.1876	0.0558	−3.3600	0.0025
ΔLNENERGY	0.6066	0.1537	3.9453	0.0006
ΔLNHYDRO	0.0382	0.0419	0.9136	0.3696

***: statistically significant at the 1% level; Source: Author's calculation results.

Based on the AIC criterion (−3.7748), the ARDL(1, 1, 1, 1) specification was identified as the optimal model for the analysis. The estimation results indicate that the ARDL model provides a satisfactory fit to the data, with an R^2 of 0.7664 and an adjusted R^2 of 0.7331. This suggests that approximately 73% - 77% of the variation in CO_2 emissions is explained by the variables included in the model. In addition, the F-statistic is significant at the 1% level, confirming the model's overall explanatory power. The Durbin-Watson statistic of 1.8867 further suggests the absence of serious autocorrelation problems, supporting the reliability of the estimated ARDL specification.

In the short run, this finding suggests that energy consumption has a positive, statistically significant impact on CO_2 emissions. Specifically, the coefficient for ΔLNENERGY is 0.6066 ($p = 0.0006$), indicating that a 1% increase in energy consumption is associated with an approximate 0.61% increase in CO_2 emissions. This finding confirms that energy consumption remains the primary driver of environmental degradation in Vietnam and reflects the economy's continued dependence on aggregate energy consumption-intensive energy sources. The result is consistent with previous empirical studies. For example, Nathaniel *et al.* [18] found that energy consumption plays a dominant mediating role between economic growth and environmental degradation, while Dogan and Inglesi-Lotz [7] also reported that increasing energy demand significantly raises CO_2 emissions in emerging economies. Similarly, Ali *et al.* [19] emphasized that economies with carbon-intensive energy structures tend to experience stronger environmental pressures from rising energy use.

Hydropower generation does not exhibit a statistically significant short-run effect on CO_2 emissions. Although the coefficient for ΔLNHYDRO is positive, its insignificance suggests that hydropower's contribution to emission mitigation remained limited during the study period. This finding may reflect the relatively modest share of hydropower within Vietnam's overall energy structure or the continued dominance of fossil-fuel-based energy consumption. The result differs from studies such as Dong *et al.* [20] and Balsalobre-Lorente *et al.* [9], which found that renewable energy contributes significantly to emission reduction. However, the present findings suggest that the environmental benefits of renewable energy may depend not only on its existence but also on its scale and integration within the national energy mix.

Economic growth exhibits a negative and statistically significant short-run relationship with CO_2 emissions, with the coefficient on ΔLNGDP estimated at -0.1876 ($p = 0.0025$). This result suggests that short-term increases in GDP may be associated with temporary improvements in production efficiency, technological upgrading, and gradual structural adjustment toward less emission-intensive economic activities. However, based on the normalized long-run estimates, economic growth does not exert a statistically significant long-run effect on CO_2 emissions within the estimated ARDL framework. This finding implies that while short-run economic expansion may coincide with transitional efficiency gains, it does not appear to systematically determine Vietnam's long-term emissions trajectory.

This result is consistent with previous empirical evidence emphasizing the context-dependent nature of the growth–environment nexus. For example, Acheampong [21] argued that the environmental consequences of economic growth depend heavily on national energy structures, technological capacity, and institutional quality. Similarly, Bekun *et al.* [22] highlighted that energy consumption often serves as the principal transmission channel through which economic growth affects environmental outcomes. Nathaniel *et al.* [18] also found that the relationship between economic growth and environmental degradation is frequently mediated by energy-use intensity and the composition of the energy mix.

The empirical findings suggest that aggregate energy consumption plays a more substantial role than economic growth or hydropower's share in electricity generation in explaining CO_2 emissions in Vietnam. The results indicate that environmental pressure is driven more strongly by the structure and intensity of energy use than by economic expansion alone. Therefore, policies aimed at reducing carbon emissions should prioritize improvements in energy efficiency, accelerated diversification toward cleaner energy sources, and broader structural transformation of the national energy system.

Table 7 presents the long-run estimation results obtained from the ARDL, FMOLS, and DOLS approaches. The comparison across estimation techniques provides additional robustness for evaluating the long-term relationship between economic growth, energy consumption, hydropower generation, and CO_2 emissions in Vietnam.

Table 7. Long-run estimation results: ARDL, FMOLS, and DOLS.

Variable	ARDL Coef.	ARDL p-value	FMOLS Coef.	FMOLS p-value	DOLS Coef.	DOLS p-value
LNGDP	0.577	0.570	−0.260	0.020	−0.234	0.000
LNENERGY	2.206	0.018	1.543	0.000	1.523	0.000
LNHYDRO	−0.400	0.483	0.012	0.866	0.029	0.488
Constant	-	-	−8.530	0.000	−8.567	0.000

Note: Values in parentheses are t-statistics (ARDL) and z-statistics (FMOLS/DOLS); Source: Author's calculation results.

The results consistently indicate that energy consumption is the most important long-run determinant of CO_2 emissions. In the ARDL model, the coefficient on LNENERGY is positive and statistically significant at the 5% level, and the FMOLS and DOLS estimators also report positive, highly significant coefficients. Specifically, the FMOLS and DOLS estimates suggest that a 1% increase in energy consumption increases CO_2 emissions by approximately 1.54% and 1.52%, respectively. The close similarity between FMOLS and DOLS coefficients demonstrates the robustness and stability of the estimated long-run relationship. These findings confirm that Vietnam's energy structure remains heavily dependent on fossil-fuel-intensive sources, making energy consumption the principal driver of environmental degradation. This result is consistent with previous studies emphasizing the dominant role of energy use in increasing carbon emissions in developing economies [7] [18].

In contrast, the long-run effect of hydropower generation remains statistically insignificant across all estimation methods. Although the ARDL model reports a negative coefficient for LNHYDRO, it is not statistically significant, whereas both FMOLS and DOLS produce coefficients close to zero and are also statistically insignificant. This consistency across estimators suggests that hydropower generation has not yet produced a sufficiently strong or stable long-run effect on reducing CO_2 emissions in Vietnam. One possible explanation is that, despite its importance as a renewable energy source, hydropower still accounts for a relatively limited share of the overall energy mix compared with fossil fuels. In addition, the environmental benefits of hydropower may be constrained by seasonal dependence, production limitations, and increasing national energy demand. Therefore, the expansion of hydropower alone appears insufficient to offset the environmental pressure generated by rapid industrialization and growing energy consumption.

The results for economic growth reveal mixed evidence across estimation approaches. In the ARDL model, the coefficient on LNGDP is positive but statistically insignificant, suggesting that economic growth does not have a stable long-run effect on CO_2 emissions. However, both FMOLS and DOLS estimates yield negative, statistically significant coefficients for LNGDP. This finding suggests that, in the long-run equilibrium relationship, economic growth in Vietnam may gradually become less emission-intensive, possibly due to improvements in energy efficiency, technological progress, or structural transformation toward less carbon-intensive sectors. The divergence between ARDL and the two cointegration estimators may reflect ARDL's greater sensitivity to dynamic adjustments and small-sample properties, whereas FMOLS and DOLS are designed to estimate the long-run equilibrium relationship more directly while correcting for endogeneity and serial correlation. Overall, the mixed evidence suggests that the relationship between economic growth and environmental quality in Vietnam remains conditional on structural and energy-related factors rather than economic expansion alone.

The robustness analysis using FMOLS and DOLS estimators further strengthens the reliability of the empirical findings. Although some coefficient magnitudes differ across estimation techniques, the overall conclusions remain broadly consistent, particularly regarding the dominant role of energy consumption in driving CO_2 emissions. The convergence of the FMOLS and DOLS estimates, especially for LNENERGY, provides strong evidence that the long-run relationship identified in the study is not merely model-specific but reflects a stable empirical pattern.

To verify the reliability and stability of the estimated ARDL model, several post-estimation diagnostic tests were conducted. The results indicate that the model satisfies the major assumptions of classical linear regression and is therefore suitable for interpretation and policy analysis.

The Breusch-Godfrey Serial Correlation LM test confirms the absence of serial correlation in the residuals. The probability values of both the F-statistic and Obs*R-squared statistic are substantially higher than conventional significance levels, indicating that the null hypothesis of no serial correlation cannot be rejected. This suggests that the dynamic specification of the ARDL(1, 1, 1, 1) model is appropriately defined and that the lag structure successfully captures the temporal dependence among variables (**Table 8**).

Table 8. Results of model diagnostic validation.

Test	Statistic	p-value	Conclusion
Breusch-Godfrey LM	0.1689	0.9190	No serial correlation
Breusch-Pagan-Godfrey	11.7963	0.1075	No heteroskedasticity
Jarque-Bera	2.4843	0.2887	Residuals are normally distributed
Ramsey RESET	0.0285	0.8674	No functional form misspecification

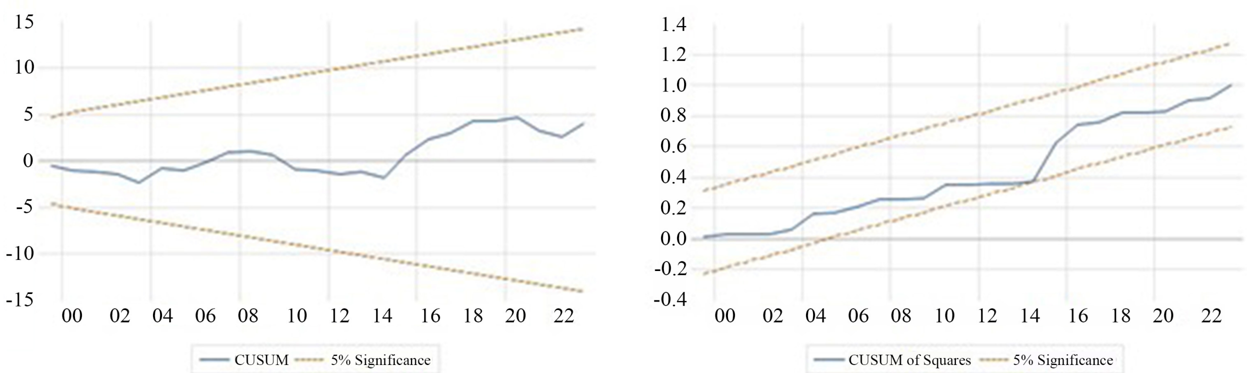
Source: Author's calculation results.

The Breusch-Pagan-Godfrey heteroskedasticity test indicates that the residuals remain homoskedastic. Since the probability values exceed the 5% significance level, there is insufficient evidence to reject the null hypothesis of constant variance. This finding implies that the estimated coefficients are efficient and that the standard errors are reliable for statistical inference.

The Ramsey RESET test indicates that the model is not misspecified for functional form. The insignificant RESET statistics indicate that no major omitted nonlinear relationships exist in the estimated equation. Therefore, the selected ARDL specification appears to provide an adequate representation of the relationship among CO_2 emissions, economic growth, energy consumption, and hydropower generation in Vietnam.

The diagnostic test results indicate that the estimated ARDL model satisfies the major assumptions of classical linear regression. The Breusch-Godfrey LM test confirms the absence of serial correlation, while the Breusch-Pagan-Godfrey test suggests that the residuals are homoskedastic. In addition, the Jarque-Bera statistic indicates that the residuals are normally distributed. The Ramsey RESET test further confirms that the model is not subject to functional form misspecification. Overall, these results support the reliability and stability of the estimated ARDL model.

The CUSUM test results show that the standardized cumulative residual curve consistently remains within the 5% significance limit throughout the entire study period. This indicates that the ARDL model parameters are highly stable and do not exhibit significant structural breaks over time. Although the CUSUM curve fluctuated slightly in some periods, particularly around 2005-2010 and 2012-2015, it remained within the acceptable test range. This result confirms that the relationship between CO_2 emissions, energy consumption, economic growth, and hydropower is not affected by short-term fluctuations or economic shocks during the study period (see Figure 1).



Source: Author's calculation results.

Figure 1. CUSUM and CUSUMSQUARE test result.

The stability of the estimated ARDL model was further examined using the CUSUM and CUSUMSQ tests. The results indicate that both the CUSUM and

CUSUM of Squares statistics remain within the 5% critical bounds throughout the sample period. This confirms the structural stability of the estimated coefficients and suggests that the model does not suffer from significant parameter instability or structural breaks. Therefore, the estimated ARDL model can be considered stable and reliable for empirical interpretation (Table 9).

Table 9. Results of the granger causality test.

Null Hypothesis	F-Statistic	Prob.
LNENERGY does not Granger-cause $LNCO_2$	0.1019	0.9035
$LNCO_2$ does not Granger-cause LNENERGY	2.7519	0.0817
LNGDP does not Granger-cause $LNCO_2$	3.1673	0.0581
$LNCO_2$ does not Granger-cause LNGDP	5.0033	0.0142
LNHYDRO does not Granger-cause $LNCO_2$	4.9373	0.0149
$LNCO_2$ does not Granger-cause LNHYDRO	4.7841	0.0167

Source: Author's calculation results.

These results imply that not only does economic growth affect the environment, but environmental factors can also have a reciprocal impact on growth. In particular, the two-way relationship between hydropower and CO_2 emissions is a significant finding, demonstrating the complex interaction between energy policy and environmental quality.

Empirical results show that energy consumption remains the primary factor driving increased CO_2 emissions, while hydropower plays a crucial role in reducing emissions, especially in the short term. These findings are not only consistent with environmental economics theory but also provide important empirical evidence for energy policy planning in Vietnam.

5. Conclusions

This study examines the relationships among CO_2 emissions, economic growth, energy consumption, and hydropower in Vietnam during 1990-2023 using the ARDL approach. The findings suggest a potential long-run interaction among the variables, while the statistically significant error-correction term indicates a stable, albeit gradual, adjustment toward equilibrium following short-run shocks. In the short run, energy consumption is associated with higher CO_2 emissions, whereas hydropower contributes to emission reduction. However, these effects are not statistically robust in the long run, suggesting that broader changes in Vietnam's energy structure may be more important in shaping long-term emission trends. Economic growth does not exhibit a statistically significant long-run effect on CO_2 emissions within the linear ARDL framework employed in this study. This implies that environmental outcomes in Vietnam may depend not only on economic expansion, but also on structural factors such as technological progress, improvements in energy efficiency, and the pace of energy transition. By distinguishing hydropower from aggregate energy consumption, this study contributes to the literature by showing that different energy sources may exert heterogeneous environmental effects and therefore should be examined separately.

The findings carry several policy implications. Reducing dependence on fossil fuels through improved energy efficiency and accelerating the transition to cleaner energy sources remains essential to mitigating emissions. Although hydropower appears to offer short-term environmental benefits, it alone is unlikely to generate substantial long-term emission reductions; therefore, a broader diversification of renewable energy sources, including wind and solar, is necessary. In addition, strengthening environmental policy instruments such as carbon pricing mechanisms and emissions trading systems could support Vietnam's low-carbon transition. At the same time, promoting structural economic transformation toward less carbon-intensive sectors will be important for achieving sustainable green growth. Finally, the study highlights the need for a more comprehensive and detailed national energy database to support future empirical research and evidence-based policymaking.

A limitation of this study is its relatively small sample size, which may reduce the Bounds test's statistical power and yield inconclusive evidence regarding cointegration. Future research could extend the analysis by incorporating nonlinear specifications, such as GDP squared, and by considering additional renewable energy sources to provide a more comprehensive assessment of Vietnam's environmental transition.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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