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An Econometric Assessment of Growth-Pollution Interactions in Vietnam within the Environmental Kuznets Framework

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ABSTRACT

Vietnam considers achieving net-zero emissions by 2050 a strategic goal, requiring a thorough understanding of the macroeconomic factors influencing greenhouse gas (GHG) emissions. This research examines the relationship between economic growth and pollution within the Environmental Kuznets Curve (EKC) framework, with a unique emphasis on the impact of real effective exchange rate (REER) volatility. Utilizing annual data from the World Bank spanning 1990 to 2024, the study employs a robust multi-step econometric methodology, primarily the ARDL bounds testing approach complemented by Granger causality analysis, to address small sample constraints and capture dynamic interactions. Additionally, a comparative Threshold Autoregression (TAR) analysis is conducted using industrialized Asian economies as benchmarks to identify Vietnam's specific EKC turning point. The findings reveal a bidirectional causal link between REER and carbon emissions, suggesting currency valuation directly affects environmental quality through trade pathways. Contrary to the classic inverted U-shaped EKC, local data show industrial growth has a linear positive effect on emissions. By referencing development benchmarks from Japan, South Korea, and Singapore, projections indicate Vietnam's EKC turning point could occur between 2044 and 2063, depending on annual growth rates of 5.8% to 3%. Based on these insights, it is recommended that Vietnam accelerate green technology adoption by offering tax incentives, streamlining administrative processes, and setting domestic standards aligned with international benchmarks to expedite progress toward its Net Zero goal by 2050.

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1. INTRODUCTION

Since the 1986 DoiMoi reforms, Vietnam's GDP has grown from $6.3 billion in 1989 to $476.3 billion in 2024, with per capita income rising from $159 to $4,700. Despite this growth, significant challenges to sustainable development remain in the region. Shultz and Peterson (2019), using the 2016 Social Sustainability Index, reported that Vietnam scored strongly in energy use and water renewal but poorly-often below 2/10-in energy saving, renewable energy, emissions, biodiversity, and land protection. These results underscore the need for targeted strategies in emission-intensive industries.

Vietnam's rapid economic growth has driven sharp increases in energy use and CO_2 emissions, which pose significant environmental challenges. Between 1994 and 2016, Vietnam submitted six national GHG inventories to the UNFCCC, covering the energy, industrial processes, agriculture, land use change and forestry, and waste sectors. The 2016 national greenhouse gas inventory reported 316,734.96 thousand tons of CO_2 equivalent, with energy accounting for 65%. The share of CO_2 increased from 39.1% to 61.3%, whereas those of CH_4 and N_2O declined (Fig. 1). These trends highlight the need for sector- and gas-specific mitigation strategies to achieve sustainable development goals.

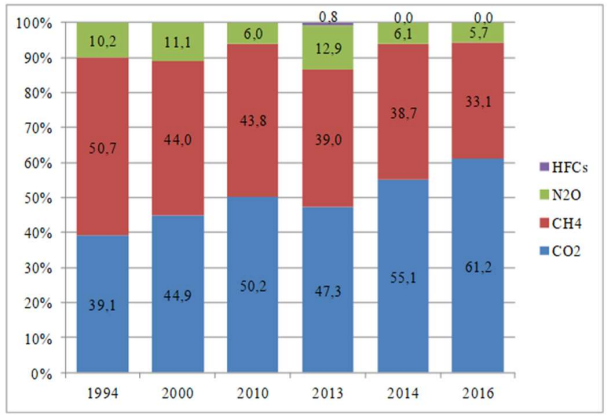


Fig. 1: Greenhouse gas emission structure by gas type in Vietnam during the period 1994-2016. Source: Vietnam National Greenhouse Gas Inventory Report.

Vietnam is among the countries most vulnerable to climate change, as highlighted by environmental assessments. In response, the government committed to achieving net-zero emissions by 2050 under the National Strategy on Climate Change, targeting a 15.8% reduction in greenhouse gas (GHG) emissions, potentially rising to 43.5% with sufficient international support.

Forecasting GHG emissions alongside economic and sustainability factors is crucial for effective environmental policies. Identifying pollution drivers helps in designing mitigation strategies that are aligned with economic conditions. This topic has attracted significant attention, and the literature is generally divided into three main research streams.

The first approach emphasizes an empirical investigation of the Environmental Kuznets Curve (EKC) hypothesis. A substantial body of literature has identified an inverted U-shaped correlation between income levels and CO_2 emissions in contexts such as China (Zhang & Cheng 2009), ASEAN countries (Pata et al. 2023), and G7 economies (Soytas & Sari 2003). Conversely, Akpan & Chuku (2011), in their analysis of Nigeria from 1960 to 2008, found a pronounced association between economic expansion and escalating environmental degradation over both short- and long-term horizons, manifesting as an N-shaped curve. Likewise, numerous studies have contested the EKC framework, particularly in developing nations (Pao & Tsai 2011, Robalino-López et al. 2015), where emerging countries sustain a linear relationship between pollution-generating activities and greenhouse gas emissions. These divergent outcomes underscore the heterogeneity of EKC validation across regions with varying levels of economic development.

The second approach focuses on identifying the relationships between actors that influence the environmental quality. It incorporates economic indicators, including GDP (Coggin 2023), GDP per capita (Kivyiro & Arminen 2014), foreign direct investment (Zhang & Zhou 2016), and trade openness (Atici 2009). Pollution is measured using total CO_2 emissions (Pao & Tsai 2011), SO_2 emissions (Coggin 2023), and ecological footprints (Thi Xuan & Thai Hung 2024). Previous studies show limited consensus, with effects differing across countries, levels of development, and periods. Sectoral contributions, particularly those of agriculture and industry (Xie et al. 2019), play a critical role in understanding CO_2 emissions in production. Ullah and Ozturk (2020) offer one of the few analyses that incorporate exchange rate dynamics as drivers of environmental pollution. However, their work focuses on correlational patterns and does not test the causality between exchange rate volatility and carbon emissions. To date, no empirical investigation has assessed the impact of exchange rate volatility on environmental quality in Vietnam.

The third approach focuses on forecasting the shape and turning point of the Environmental Kuznets Curve (EKC) in future scenarios. Within this framework, scholars have constructed empirical models to estimate the time horizon and resource requirements necessary for an economy to achieve specific environmental objectives (Robalino-López et al. 2015). This methodology has also been applied to forecast the outcomes of prospective policies, such as an emissions trading scheme and a carbon tax (Coxhead et al. 2013).

In Vietnam, several studies have evaluated the Granger causality relationship using Vector Autoregression (VAR) estimation (Pham & Tuan 2022), Autoregressive Distributed Lag (ADRL) (Đoàn 2024), or wavelet coherence analysis (Trần Văn Hưng 2024) to assess the relationship in both the short and long terms. Inconsistencies in analytical outcomes often arise from divergent data processing techniques, even when they are applied to identical datasets. These discrepancies likely reflect the differences in data coverage and methodology. Employing multiple estimation techniques may help to reconcile such inconsistencies and provide clearer insights. To address this methodological challenge, the present study employs a combined approach, integrating the VAR and ARDL models to enhance the robustness of the short- and long-term relationship estimations.

In addition, a critical gap remains in the literature regarding the transmission mechanism of monetary factors, specifically exchange rate volatility, on environmental degradation in transition economies such as Vietnam. Given Vietnam's high trade openness, where total trade turnover frequently exceeds 150% of GDP, exchange rate fluctuations play a pivotal role in determining the cost of imported

technology and the competitiveness of carbon-intensive exports. Existing studies often overlook this bidirectional relationship. Furthermore, traditional EKC estimations for Vietnam often fail to identify a turning point because of the linear nature of current historical data. Therefore, an approach that combines robust short-run estimations (ARDL) with comparative threshold benchmarking (TAR) is required to provide a realistic roadmap for the Net Zero 2050 target.

To address these research gaps, this study integrates three analytical approaches to examine the structure of the Environmental Kuznets Curve (EKC) and explore the relationship between economic growth and carbon dioxide emissions. It further develops empirical scenarios to estimate the EKC turning point in Vietnam. Specifically, this study aims to investigate the following questions:

- How do the relationships between CO_2 emissions and relevant factors evolve over the short and long term?
- In what ways do economic growth indicators (GDP growth, foreign direct investment and trade openness) and sustainable development variables (urban population size, industrial structure) influence CO_2 emissions?
- When will Vietnam achieve its Net Zero target under various economic growth scenarios?

2. THEORETICAL BASIS

2.1. Environmental Kuznets Curve (EKC) Theory

One of the popular theories explaining the relationship between economic growth and environmental degradation is the Environmental Kuznets Curve (EKC), proposed by Kuznets (Kuznets 1955). This concept posits a non-linear, inverted U-shaped relationship between per capita income and environmental degradation. In the early stages of development, pollution increases alongside rapid industrialization and urbanization. As economies transition to high-tech and service-based sectors, emissions typically decline. The EKC framework suggests that economic growth initially exacerbates environmental harm but may ultimately lead to improvements as income levels increase.

2.2. Greenhouse Gas (GHG) Emissions

Greenhouse gases (GHGs) are atmospheric compounds that absorb long-wave infrared radiation emitted from the Earth's surface after sunlight exposure, then re-radiate heat back toward the surface, contributing to the greenhouse effect. The main GHGs include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs). In Vietnam, CO_2 accounts for over 50% of total emissions according to the latest GHG inventory reports, making it the primary contributor to national greenhouse gas output.

2.3. Impact of Economic Growth on GHG Emissions

Economic growth refers to the expansion of an economy's size and rate over a given period, typically measured by GDP, GDP per capita, and annual GDP growth (Pham & Tuan 2022). Economic development increases GHG emissions due to broad-based industrial activity. Although many studies confirm a non-linear relationship between economic growth and CO_2 emissions, where pollution rises at early stages and falls after income exceeds specific thresholds (Pao & Tsai 2011, Xie et al. 2019, Trần Văn Hưng 2024), others reject the EKC hypothesis, reporting a persistently positive association between GDP and pollution. This pattern has been observed in developing countries such as Vietnam. (Al-Mulali et al. 2015) or Nigeria & Venezuela (Soytas & Sari 2003). In particular, some studies have even found no link between rising GHG emissions and economic growth (Zhang & Cheng 2009, Kivyiro & Arminen 2014). While some countries have reduced emissions through green and nuclear energy, Vietnam's industrialization drives emission volatility, necessitating continuous evaluation of macroeconomic impacts on pollution.

2.4. Impact of Foreign Direct Investment (FDI) on GHG Emissions

Foreign direct investment (FDI) plays a crucial role in developing economies like Vietnam, expanding production capacity and enabling technology transfer. However, its environmental impact remains contested. Studies such as Kivyiro & Arminen (2014) and Pao & Tsai (2011) report that FDI correlates with higher CO_2 emissions, reported multinational firms may shift polluting activities to countries with weaker environmental standards. Conversely, Zhang & Cheng (2009) highlighted cases where FDI facilitates cleaner technologies, reducing emissions. Thus, the EKC hypothesis linking FDI and CO_2 emissions remains debated.

In Vietnam, findings are similarly mixed. Trần Văn Hưng (2024) concludes that FDI increases emissions in both the short and long run, while Đoàn (2024) identifies only short-term effects, leaving long-term impacts unresolved. In contrast, Xuan (2025) identified a dual role of FDI in relation to CO_2 emissions: in the short term, it contributes to higher emissions through manufacturing expansion, while in the long term, it holds potential to reduce emissions by facilitating cleaner technologies. Thus, evidence on the impact of FDI on CO_2 emissions in Vietnam remains inconclusive, largely due to variations in data coverage and methodological approaches. Applying multiple estimation

techniques may help resolve these inconsistencies and yield more robust insights.

2.5. Impact of Exchange Rate on GHG Emissions

According to Ullah & Ozturk (2020), exchange rate volatility affects domestic production, investment, money demand, trade balance, and economic growth, potentially harming the environment. A weaker currency boosts exports, whereas a stronger currency makes imports cheaper. Their study in Pakistan indicated that positive exchange rate shocks reduce emissions, whereas negative shocks increase them. In Pakistan, elevated public debt and heavy dependence on the IMF and bilateral loans can trigger significant volatility in exchange rates. In contrast, foreign capital plays a modest role in Vietnam's economy. Therefore, the impact of exchange rate volatility on CO_2 emissions may differ. Moreover, previous studies have not empirically investigated the causal relationship between exchange rates and environmental pollution, focusing primarily on correlations (Wang et al. 2024). This raises an important question: Is there a causal relationship between these variables, particularly in the context of emerging economies such as Vietnam?

2.6. The Impact of Industrialization on GHG Emissions

Industrial growth, which is heavily dependent on fossil fuels such as coal and gas, contributes significantly to CO_2 emissions, particularly when outdated technologies and polluting raw materials are used (Ullah et al. 2021). While many studies confirm a positive link between industrialization and emissions (Xie et al. 2019), other studies emphasize the potential for emission reductions through technological innovation and cleaner production methods (Zhang & Zhou 2016, Robalino-López et al. 2015). In Vietnam, studies have revealed a U-shaped EKC curve in the short term, suggesting that early industrial growth exacerbates pollution through outdated technologies and inefficient energy use, whereas later stages hold potential for improvement (Đoàn et al. 2023). This finding contrasts with the inverted U-shaped relationship observed in Ghana (Kwakwa and Alhassan 2018). However, studies on Vietnam remain limited, with Ullah et al. (2021) confirming only short-term pollution effects before the COVID-19 pandemic and before the country made net-zero commitments. A comprehensive reassessment of industrial impacts is essential for informing future environmental strategies and supporting sustainable development goals.

3. MATERIALS AND METHODS

3.1. Data Sources

This study examines Vietnam's data from 1990 to 2024, drawing from reputable sources such as the World Bank and the European Commission's EDGAR database (Emissions Database for Global Atmospheric Research). The selected variables include Carbon Emissions per capita (CPC), GDP per capita (GPC), Foreign Direct Investment (FDI), Real Effective Exchange Rate (REER), and Industrial Value Added. CPC, GPC, and REER are transformed into natural logarithms to interpret coefficients as elasticities. FDI and Industrial Value Added are expressed in their original percentage units (%) to accurately reflect the direct influence of

Table 1: Data sources.

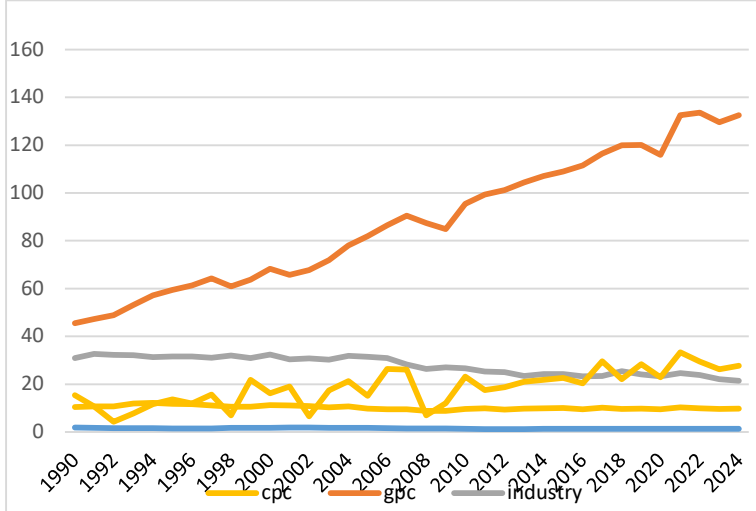
	Abbreviation	Description	Units of measurement	Source
Dependent variable	CPC	Total carbon dioxide (CO2) emissions (total) excluding LULUCF	Metric Tons	WDI
Independent variable	GPC	GDP per capita, PPP (International Fixed Price 2021)	USD	WDI
	FDI	Foreign Investment Inward/ GDP	%	WDI
	REER	Real effective exchange rate index (2020 = 100 points)	points	WDI
	Industry	Industrial (including construction) value added / GDP	%	WDI

Source: World Bank database

Table 2: Data statistical description.

Variables	Observations	Mean	Standard error	Min	Max
LnCPC	35	0.2046817	.7880595	-1.172155	1.312754
LnGPC	35	8.726135	.526576	7.811149	9.576039
FDI	35	5.382016	2.147019	2.781323	11.93948
LnREER	35	9.700555	0.3206257	8.785326	10.09266
INDUSTRY	35	34.60179	4.380435	22.67429	40.20875

* Note: Ln stands for Logarithmic Function Form; Source: Authors' compilation



Source: Authors' compilation.

Fig. 2: Trends of variables during the period 1990-2024. Source: Authors' compilation.

structural shares on emissions, adhering to standard econometric practices for ratio variables. The study intentionally focuses on total CO_2 emissions per capita, excluding the "Land Use, Land-Use Change, and Forestry" (LULUCF) sector. This allows the analysis to isolate emissions directly resulting from key economic activities such as industry, energy use, and transportation—sectors closely linked to GDP growth, FDI, and trade. This approach improves the model's accuracy and ensures the results meaningfully capture the true relationships under investigation.

Tables 1 and 2 present the data sources and descriptive statistics for the model variables. Fig. 2 illustrates the trends of the variables during the study period.

3.2. Estimation Method

This study employs a comprehensive multi-step econometric framework to analyze the complex and evolving relationship between economic growth and greenhouse gas (GHG) emissions in Vietnam, capturing both short-term fluctuations and long-term equilibrium trends. The methodology integrates five complementary approaches: Vector Autoregression (VAR), the Johansen cointegration test with the Vector Error Correction Model (VECM), the Autoregressive Distributed Lag (ARDL) model, the Granger causality test, and the Threshold Autoregression (TAR) model. The VAR framework offers an initial overview of variable interdependencies and shock transmission, while the Johansen test and VECM are used to identify and model long-run cointegration relationships. The ARDL model is the primary estimation technique because of its effectiveness with mixed I(0) and I(1) variables, enabling reliable short- and long-term coefficient estimation even with limited data samples. The bounds test verifies the presence of cointegration prior to estimation, and the error correction model derived from ARDL captures the speed of adjustment of GHG emissions to short-term shocks. Additionally, the VAR approach helps determine appropriate lag structures and visualize shock propagation. Granger causality tests clarify the directionality of relationships, such as between exchange rates and emissions, which regression coefficients alone cannot reveal. Because Vietnam's historical data currently lie on the upward slope of the EKC and lack a clear turning point, a comparative Threshold Autoregression (TAR) model is used. Instead of estimating an elusive threshold from local data, this approach analyzes the turning points of reference economies—Japan, South Korea, and Singapore—to project Vietnam's potential future trajectory.

4. RESULTS

4.1. Units Root Test

The ADF and PP unit root tests (Table 3) consistently indicate that all series, LnCPC, LnGpc, FDI, LnReer, and Industry, are non-stationary in levels but become stationary after first differencing, demonstrating they are integrated of order one, I(1). This is methodologically significant because using OLS on level data can lead to spurious regression results, where statistical significance does not imply causality. Confirming the I(1) nature of these series validates the use of models capable of analyzing long-term relationships, such as VECM and ARDL, which are specifically designed to manage non-stationary time series.

Selecting the optimal lag length is a crucial step that ensures the reliability of both cointegration tests and subsequent estimation models. An excessively short lag may omit key dynamic effects, leading to autocorrelation errors, whereas an overly long lag can reduce degrees of freedom and estimation efficiency-particularly in small samples. Table 4 shows that a lag length of four is consistently supported by all major information criteria, including AIC, SC, HQ, LR, and FPE. Notably, the more conservative criteria (SC and HQ), which heavily penalize additional parameters in small samples, also select lag 4, indicating genuine explanatory gains rather than overfitting. Therefore, this lag order is adopted as the basis for subsequent tests and estimations to ensure the exhaustive capture of the dynamic relationships among the variables.

Using the VAR model, we examined the short-term drivers of greenhouse gas emissions. The results show that per-capita carbon emission growth (ΔlnCPC) is strongly influenced by economic growth (ΔlnGPC), with a significant first lag indicating the cumulative effects of recent expansion. Industrial activity, measured by industry (% GDP), also emerges as a key contributor to rising emissions. Overall, the analysis provides clear evidence that Vietnam's industrialization-led growth from 1990 to 2024 has been closely linked to escalating carbon emissions.

4.2. Estimation of the ARDL Model

The Autoregressive Distributed Lag (ARDL) model was employed as the primary estimation method to identify the key factors influencing carbon emissions in Vietnam. This

Table 3: Results of ADF and PP unit tests.

	LnCPC		LnGPC		FDI		LnREER		INDUSTRY	
	ADF	PP	ADF	PP	ADF	PP	ADF	PP	ADF	PP
Unit root test of the variables at the standard level										
Intercept	-0.454635	-0.46979	-1.558	-2.209	-2.85903*	-2.664191*	-1.936926	-3.7398***	-2.948018*	-3.918707**
	(0.8893)	(0.8864)	(0.4922)	(0.2069)	(0.0620)	(0.0907)	(0.3120)	(0.0078)	(0.0521)	(0.0288)
Intercept and trend	-1.607263	-2.035115	-3.03385	-1.690	-3.356985*	-3.026803	-1.646705	-6.0271***	-3.192135	-2.314420
	(0.7718)	(0.5644)	(0.1387)	(0.7334)	(0.0749)	(0.1400)	(0.7519)	(0.001)	(0.1063)	(0.4153)
Unit root test of the variables at first difference										
Intercept	-3.9977***	-3.99***	-4.359***	-4.401***	-3.7454***	-5.0675***	-5.8398***	-11.450***	-4.8735***	-4.858436***
	(0.0037)	(0.0037)	(0.0016)	(0.0014)	(0.0080)	(0.0002)	(0.0000)	(0.0000)	(0.0004)	(0.0004)
Intercept and trend	-3.9170***	-3.9170	-4.7120***	-4.677***	-3.69417**	-5.0159***	-6.25347**	-9.9875***	-5.3198***	-5.320650***
	(0.0209)	(0.0209)	(0.0033)	(0.0036)	(0.0374)	(0.0015)	(0.0001)	(0.0000)	(0.0007)	(0.0007)

Note: *, **, *** indicate rejection of the null hypothesis (non-stationarity) at the 10%, 5%, and 1% significance levels, respectively. Lag length is determined based on the Akaike Information Criterion (AIC), with p-values reported in parentheses.

Source: Authors' compilation.

Table 4: The lag selection criteria**.**

Lag	LogL	LR	FPE	AIC	SC	HQ
0	72.4428	NA	7.67e-09	-4.496191	-4.42147*	-4.421482
1	112.990	64.87555*	2.80e-09*	-5.532672	-5.08442	-5.084417
2	130.369	22.01402	5.41e-09	-5.024639	-4.20284	-4.202838
3	149.169	17.54678	1.26e-08	-4.611314	-3.41596	-3.415967
4	210.746	36.94623	3.18e-09	-7.049783*	-5.48091*	-5.480891*

LR: Sequential modified LR test statistic (each test at 5% level)
FPE: Final prediction error
AIC: Akaike criterion
SC: Schwarz criterion
HQ: Hannan-Quinn information criterion
After determining the optimal lag length of 4, the study estimates the Vector; Source: Authors' compilation.

Table 5: Estimation of ARDL model regression coefficients (4, 3, 4, 3, 4).

ARDL (4, 3, 4, 3, 4)		
	Regression coefficient	Standard Error
Panel A: Short-term effect		
Intercept	-26.26047***	3.757535
t-1	-0.048092	0.138171
t-2	0.665829***	0.1476112
t-3	0.674352***	0.194053
t	1.666199***	0.501172
t-1	3.319981***	0.551535
t-2	0.827663	0.618099
t	1.595479***	0.291030
t-1	-0.577660*	0.271511
t-2	0.367064	0.291855
t-3	0.204579	0.163849
t	0.029525***	0.005955
t-1	-0.025076***	0.007314
t-2	-0.012913**	0.004583
t	-0.004087	0.005492
t-1	-0.008872	0.007269
t-2	0.025001***	0.005634
t-3	0.026085***	0.006907
ECt-1	-0.184342***	0.000000
Panel B: Long-term effect		
LnGPCt-1	0.720026*	0.0542
FDIt-1	0.077224**	0.0282
LnREERt-1	1.646606**	0.0474
INDUSTRYt-1	0.038326***	0.0011

Note: *, **, *** indicate statistical significance at the corresponding significance levels of 10%, 5%, 1%. Source: Authors' compilation.

approach is particularly suitable for small sample sizes, such as the 35 annual observations used in this study, thereby enhancing the robustness and reliability of the estimation results.

Table 5 shows the key drivers of Vietnam's per-capita CO_2 emissions. In the long run (Panel B), economic growth (LnGpc) remains the dominant factor, with a significant coefficient of 0.72, indicating that a 1% increase in GDP per capita increases CO_2 emissions by approximately 0.72%. Foreign direct investment and industrial output (Industry) also exert significant positive effects, confirming that industrialization and FDI inflows into manufacturing have intensified environmental pressures. The real exchange rate (LnReer) also shows a positive long-run association with emissions.

In the short run (Panel A), the error correction term (ECt–1) of –0.184 ($p < 0.01$) confirms a stable long-run equilibrium, implying that approximately 18.4% of the disequilibrium is corrected annually. This moderate adjustment rate suggests that full re-equilibration will take more than five years to achieve.

Overall, the ARDL results consistently indicate that Vietnam's growth path remains closely linked to industrialization, FDI attraction, and rising CO_2 emissions, providing a robust empirical basis for formulating sustainable policy interventions.

4.3. Diagnostic Test

The reliability of the linear ARDL model estimation was verified through a series of diagnostic tests assessing serial autocorrelation, heteroscedasticity, non-normality, and model specification errors. The test results, summarized in Table 6, indicate that the model is free from specification errors, heteroscedasticity, autocorrelation, and non-normal residual distribution at the 5% significance level or lower.

4.4. Granger Causality Test

The Granger causality results in Table 7 highlight several short-run dynamic relationships among carbon emissions per capita (CPC), industrialization (INDUSTRY), real effective exchange rate (REER), foreign direct investment (FDI), and economic growth (GPC) in Vietnam. A bidirectional link exists between the REER and CPC, showing that exchange rate fluctuations influence trade and production costs, whereas higher emissions from energy-intensive industries can affect exchange rate movements through export competitiveness. Similarly, FDI and REER display bidirectional causality, suggesting that stable exchange rates attract investments, whereas large inflows can pressure the currency.

Unidirectional causality from INDUSTRY to CPC confirms that industrial expansion drives emissions, reflecting the carbon-intensive manufacturing sector in Vietnam. FDI also Granger-causes CPC, consistent with the "pollution haven" hypothesis, wherein foreign investment worsens environmental degradation. Economic growth strongly Granger-causes CPC at the 1% level, while the

Table 6: Diagnostic test results.

Serial correlation	c2(2) = 1.379835
	P value (0.55772)
Heteroskedasticity	F – statistic = 0.6575
	P value (0.4858)
RESET test	P value (0.1321)
Normality	Jarque – Bera = 1.495199
	P value (0.473502)

Source: Authors' compilation.

reverse does not, underscoring that Vietnam's expansion relies heavily on energy consumption and emission-intensive activities. This supports the early stage of the Environmental Kuznets Curve (EKC), in which development initially worsens environmental quality.

Overall, the findings reveal close interdependence between macroeconomic factors and emissions, stressing the need for green industrial restructuring, sustainable FDI strategies, and effective exchange rate management to achieve low-carbon growth.

4.5. Comparative Threshold Benchmarking

Since Vietnam's current economic data show a linear relationship with emissions, it is not statistically feasible to estimate the EKC turning point endogenously using local data. To address this challenge, the study employs a comparative benchmarking approach with the Threshold Autoregression (TAR) framework, applied to reference economies: Japan, South Korea, and Singapore.

Annual time-series data on GDP per capita (constant 2020 PPP International dollars) and CO2 emissions per capita for these countries were sourced from the World Bank database. TAR estimations on these industrialized Asian economies allowed us to empirically determine the specific income thresholds at which their emission trends reverse or decouple from growth. These empirically identified thresholds (see Table 8) serve as benchmarks for projecting Vietnam's sustainable development trajectory under various growth scenarios.

This study evaluates Vietnam's growth prospects using a variety of forecasting methods, including traditional ARIMA models and advanced machine learning techniques such as Prophet and LSTM. As illustrated in Fig. 3, ensemble forecasts indicate a generally sustainable upward trend in GDP per capita extending to 2050, although long-term projections differ considerably. Prophet suggests a moderate, nearly linear growth trajectory, implying potential stabilization. ARIMA provides a baseline forecast based on historical data, while LSTM predicts a steeper increase, reflecting the influence of recent economic momentum. These differing models underscore that Vietnam's future growth will largely depend on policy choices that shape its long-term sustainability.

Building on the experiences of advanced economies and recognizing Vietnam's advantage as a latecomer in adopting new technologies, this study estimates that the country's economic inflection point may occur at a gross

Table 7: Granger causality test results**.**

Null Hypothesis:	Obs	F-Statistic	Prob.
LNREER does not Granger Cause LNCPC	35	3.043230*	0.063689
LNCPC does not Granger Cause LNREER		4.293021**	0.023648
INDUSTRY does not Granger Cause LNCPC	35	2.5257334*	0.098071
LNCPC does not Granger Cause INDUSTRY		1.1003225	0.346725
FDI does not Granger Cause LNCPC	35	0.453356**	0.040074
LNCPC does not Granger Cause FDI		1.6878016	0.203199
LNGPC does not Granger Cause LNCPC	35	5.6597***	0.008624
LNCPC does not Granger Cause LNGPC		1.54219482	0.231536
INDUSTRY does not Granger Cause LNREER	35	1.5091403	0.23854
LNREER does not Granger Cause INDUSTRY		0.9854921	0.38583
FDI does not Granger Cause LNREER	35	4.765037**	0.016553
LNREER does not Granger Cause FDI		4.072633**	0.028021
LNGPC does not Granger Cause LNREER	35	2.45213603	0.104395
LNREER does not Granger Cause LNGPC		0.09160786	0.912735
FDI does not Granger Cause INDUSTRY	35	2.2161103	0.127802
INDUSTRY does not Granger Cause FDI		1.6455498	0.211018
LNGPC does not Granger Cause INDUSTRY	35	0.572067	0.570815
INDUSTRY does not Granger Cause LNGPC		0.256411	0.775620
LNGPC does not Granger Cause FDI	35	1.8309641	0.178932
FDI does not Granger Cause LNGPC		0.1291161	0.879392

Note: *, **, *** indicate statistical significance at the corresponding significance levels of 10%, 5%, 1%.
Source: Authors' compilation.

Table 8: Thresholds for Emission Trend Reversal in Japan, South Korea, and Singapore.

Country	GDP per capita (International Fixed Prices 2020)
Japan	41596.9238**
South Korea	38698.4611**
Singapore	57213.0978*

Note: *, **, *** significant at 10%, 5%, 1%.
Source: Authors' compilation

per capita income of approximately USD 45,500. This benchmark reflects both the structural challenges typical of developing economies and the emerging opportunities in green technology. Currently, Vietnam's GPC stands at USD 14,415, and three growth scenarios have been developed to evaluate potential policy impacts (see Table 9). The Growth Scenario, with an annual growth rate of 5.8%, projects that income will reach USD 45,500 by 2045, though it may entail higher emissions without strict controls. The Business-as-Usual Scenario, growing at 4.5%, aligns with national targets and aims to achieve this milestone by 2050. The Conservative Scenario, at a 3% growth rate, delays convergence until 2063, reducing short-term emissions but limiting green investment capacity and progress toward Net Zero 2050.

5. DISCUSSION AND RECOMMENDATIONS

The Granger causality test indicates a unidirectional causal relationship from GPC to CPC at the 1% significance level ($p = 0.0086$), confirming that economic growth influences carbon emissions in Vietnam. The short-term ARDL results show several positive and statistically significant lagged GPC terms, implying that an increase in GDP per capita leads to higher CO_2 emissions. The error correction term (ECt-1 = –0.1843, $p < 0.01$) demonstrates convergence toward the long-run equilibrium. In the long run, the coefficient of

Table 9: Proposed scenario.

Scenario	GDP growth	Required years
Positive	5.8%	20 years
Neutral	4.5%	26 years
Negative	3%	39 years

Source: Authors' compilation

LnGPCt-1 = 0.7200, $p < 0.1$, remains positive, suggesting that economic growth continues to increase emissions. Overall, these findings suggest that Vietnam's growth pattern remains energy- and carbon-intensive, and the turning point of the Environmental Kuznets Curve has not yet been achieved. Promoting green investments, renewable energy, and cleaner industrial practices is crucial for decoupling economic development from environmental harm. These results align with the findings of Đoàn Ngọc Phúc (2024) and Atici (2009), but contrast with Trần Văn Hưng (2024), who argued that long-term economic growth would eventually lead to a decline in CO_2 emissions. Consequently, developing countries like Vietnam should adopt policies that maintain economic growth while protecting environmental quality. Rapid industrialization risks causing long-term ecological damage, highlighting the importance of planning industrial zones with sector-specific environmental standards that meet international benchmarks to reduce GHG emissions.

This study also provides evidence of causality running from Industrialization and FDI to per capita carbon emissions, with no indication of the reverse. These findings align with those of Le et al. (2016) and Xie et al. (2019), yet they differ from the results of Jalil & Mahmud (2009) and Ullah et al. (2021), who did not find a long-term relationship. Vietnam's FDI policies increasingly focus on attracting modern, cleaner technologies (Zhang & Cheng 2009), maintaining Industrialization and FDI as significant contributors to pollution.

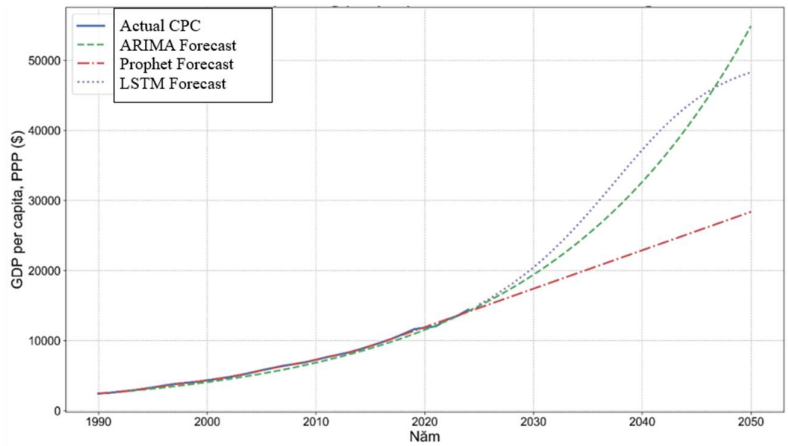


Fig. 3: Analysis of GDP per capita scenarios in Vietnam, 1990 – 2050. Source: Authors' Compilation.

The findings demonstrate a positive and statistically significant association between the real effective exchange rate (REER) and per capita carbon emissions (CPC) in both the short and long term. The ARDL analysis reveals that short-term exchange rate shocks lead to increased emissions ($\beta = 1.60$, $p < 0.01$), while the long-term coefficient remains positive and significant ($\beta = 1.65$, $p < 0.05$). Recent macroeconomic developments support this pattern: the Vietnamese currency depreciated approximately 5% in 2024 and an additional 3.4% in 2025, coinciding with a roughly 10% weakening of the US dollar. In the short run, currency depreciation boosts export competitiveness and drives industrial growth, which can raise carbon emissions. Over the long term, sustained depreciation may reinforce reliance on carbon-intensive industries and hinder the shift to cleaner technologies. Granger causality tests further indicate bidirectional causality between REER and CPC, implying that exchange rate fluctuations both influence and respond to emission dynamics through trade, production, and energy consumption channels. These results are consistent with findings from China (Wang et al. 2024) but differ from those of Ullah and Ozturk (2020), supporting the notion that growth driven by price competitiveness—instead of technological progress—tends to exacerbate environmental problems in developing economies.

The bidirectional causality between the real exchange rate (LnREER) and emissions (LnCPC), as well as between foreign direct investment (FDI) and LnREER, indicates that exchange rate policies have a direct impact on environmental outcomes and capital inflows. This relationship suggests that exchange rate fluctuations can serve as predictors or influencers of environmental pollution. Consequently, maintaining macroeconomic stability while encouraging green investments and low-carbon production is vital for Vietnam's Net Zero 2050 goal. Exchange rate management should incorporate environmental considerations, as currency volatility directly affects production methods and emission intensity. Furthermore, industrialization and FDI strategies must prioritize environmentally friendly, high-value projects to avoid harmful capital inflows that could destabilize the currency. These findings underscore the importance of coordinated macroeconomic, trade, and environmental policies to prevent feedback effects and promote sustainable development. In open economies, FDI and industrialization remain crucial drivers of growth and, over time, can also enhance environmental quality through technology transfer and corporate social responsibility aligned with international standards.

6. CONCLUSIONS

Using data from Vietnam for the period 1990–2024 and employing both the validation of the EKC hypothesis and Granger causality analysis, this study confirms the existence of a bidirectional causal relationship between the real exchange rate and CO_2 emissions in the long run. Therefore, exchange rate management can serve as an effective policy instrument for forecasting and enhancing the effectiveness of environmental protection measures. In addition, the short- and long-term effects of industrial development, FDI, and economic growth on CO_2 emissions are characterized by a traditional U-shaped relationship. However, the EKC turning point has not yet emerged in Vietnam, indicating that economic expansion continues to drive the increasing environmental pressure. Empirical projections indicate that Vietnam's EKC turning point is likely to occur between 2044 and 2063, depending on annual growth scenarios ranging from 5.8% to 3%. Based on these findings, Vietnam should promote the adoption of green technologies through supportive tax incentives, streamlined administrative procedures, and domestic production standards aligned with international benchmarks to advance the implementation of its Net Zero objective by 2050.

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