

Examining Growth Transitions and Environmental Quality Through Dynamic Threshold Modeling in Southeast Asia

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Abstract. This study investigates the nonlinear relationship between economic growth and environmental quality across 11 Southeast Asian countries during 2015 – 2024 using a Dynamic Panel Threshold Model (DPTM) within a data-driven sustainability framework. Drawing on integrated datasets from the World Development Indicators (WDI) and the U.S. Energy Information Administration (EIA), the model captures threshold effects in the growth – environment nexus and tests the Environmental Kuznets Curve (EKC) hypothesis. The results reveal a turning point at an income per capita of USD 14,875 for the full sample: below this level, growth increases CO₂ emissions; above it, growth reduces emissions, indicating a transition toward greener development. For developing economies (threshold USD 5,480), growth remains emission-intensive, while in developed members (threshold USD 39,620), growth contributes to emission reduction. Energy use, trade openness, and FDI significantly influence emissions, confirming the presence of a “pollution haven” effect in emerging markets. By integrating dynamic modeling with real-time environmental data systems, this research contributes to informatics-based environmental policymaking, offering evidence-based guidance for ASEAN countries to accelerate clean-energy transition, attract green investment, and strengthen environmental governance.

Keywords: Economic Growth; Environmental Quality; Environmental Kuznets Curve (EKC); Dynamic Panel Threshold Model (DPTM); Southeast Asia

1. Introduction

Over the past three decades, Southeast Asian countries have experienced rapid economic growth, leading to remarkable improvements in living standards, poverty reduction, and regional integration into the global economy (ADB, 2020; World Bank, 2024). However, this economic dynamism has also generated substantial environmental pressures, including rising greenhouse gas emissions, deteriorating air quality, and the depletion of natural resources (Shafik & Bandyopadhyay, 1992; Stern, 2004; Li, Zhu & Zhang, 2025). In Vietnam and several neighboring economies, the accelerated pace of industrialization and urbanization continues to challenge national sustainability agendas (Nguyen & Nguyen, 2021; Onifade & Alola, 2022; Ullah, Adebayo, Irfan & Abbas, 2023).

A widely used theoretical framework for exploring the interplay between economic growth and environmental quality is the Environmental Kuznets Curve (EKC) hypothesis. EKC suggests that environmental degradation initially rises with income growth but eventually declines after reaching a specific income threshold, as economies adopt cleaner technologies and implement stronger environmental regulations (Grossman & Krueger, 1995; Dinda, 2004). Nonetheless, empirical findings remain inconsistent, particularly for Southeast Asian countries, where disparities in economic structure, energy dependency, and policy enforcement complicate this relationship (Saboori, Sulaiman & Mohd, 2012; Al-Mulali, Saboori & Ozturk, 2015; Zhang, Wang & Guo, 2024).

To address these limitations, this study applies a Dynamic Panel Threshold Model (DPTM) to 11 Southeast Asian economies from 2015 to 2024. Unlike traditional linear or static EKC analyses, the DPTM enables the identification of nonlinear income thresholds and captures time-varying interactions between growth, energy use, and institutional quality allowing for a more dynamic understanding of sustainability transitions. By leveraging recent datasets from the World Development Indicators (WDI) and U.S. Energy Information Administration (EIA), the analysis integrates high-frequency economic and environmental indicators within a data-informed sustainability framework.

Unlike prior EKC studies, this paper highlights the value of informatics-based monitoring systems for environmental governance and green logistics in ASEAN. The results aim to provide evidence-driven insights into how data systems can support regional sustainability planning, cross-border pollution management, and low-carbon economic strategies, offering both methodological and policy contributions to Southeast Asia's data governance and sustainable development discourse.

2. Literature Review

2.1. Theoretical Foundations

The relationship between economic growth and environmental quality has been explored through multiple theoretical frameworks, the most traditional being the Environmental Kuznets Curve (EKC) hypothesis. According to EKC, during the early stages of industrialization, economic growth tends to intensify pollution and resource depletion as production relies heavily on energy-intensive industries (Grossman & Krueger, 1995). However, after per capita income surpasses a certain threshold, economies generally transition toward cleaner technologies, improved regulatory frameworks, and more service-oriented structures, leading to environmental improvement (Dinda, 2004; Stern, 2004).

Beyond the classical EKC, complementary theories emphasize the mediating roles of energy transition and institutional quality. The energy transition perspective posits that as the share of renewable energy in total energy consumption increases, the marginal environmental cost of growth declines (Apergis & Payne, 2010). Meanwhile, institutional and environmental governance theories suggest that strong, transparent institutions and effective regulatory systems can mitigate pollution even before reaching the

income threshold (Dasgupta et al., 2001). These frameworks collectively highlight that both technological advancement and governance capacity determine whether economic development leads to environmental improvement or deterioration.

Technological and Informatics Perspectives on EKC

Recent research introduces a new dimension to the EKC debate by linking digitalization, environmental informatics, and sustainability transitions. Advances in data-driven monitoring technologies such as carbon informatics, environmental IoT sensors, and satellite-based emissions tracking have enabled real-time assessment of environmental impacts (Zhang et al., 2024; Li et al., 2025). These systems help governments and firms optimize energy consumption, enhance supply chain transparency, and adopt predictive analytics for pollution control. The emergence of green logistics systems and digital sustainability platforms across ASEAN has also accelerated the EKC turning point by allowing policymakers to make timely, evidence-based interventions. Incorporating informatics into environmental management not only strengthens accountability but also aligns with ASEAN's broader data governance and regional sustainability frameworks.

Methodological Implications and Rationale for DPTM

Methodologically, earlier studies testing the EKC relationship often relied on static or linear regression models using GDP and emissions data. However, these models assume parameter homogeneity and fail to capture dynamic feedback effects or structural breaks that occur as economies evolve. Traditional fixed-effect and random-effect approaches overlook heterogeneity in industrial maturity, digital infrastructure, and institutional capacity among ASEAN countries.

The Dynamic Panel Threshold Model (DPTM) addresses these limitations by allowing endogenous detection of threshold values points at which the impact of growth on environmental quality changes in both direction and magnitude (Hansen, 1999; Chimeli & Braden, 2001; Kremer, Bick & Nautz, 2013). Unlike static frameworks, DPTM captures dynamic inertia (where past environmental conditions influence current outcomes) and accounts for the nonlinear, country-specific pathways of economic development. This makes DPTM particularly suitable for ASEAN economies, which differ widely in their levels of industrialization, renewable energy adoption, and digital readiness. Therefore, DPTM offers an empirically robust and policy-relevant tool for analyzing the complex interactions between growth, technology, and environmental quality in a data-informed sustainability context.

2.2. Empirical Studies

Globally, numerous studies have provided mixed evidence on EKC. Shafik & Bandyopadhyay (1992) and Grossman & Krueger (1995) presented initial evidence suggesting that growth can improve the environment after reaching a certain income threshold. However, Stern (2004) and Carson (2010) argued that the results depend heavily on the type of environmental indicator, model, and data scope. Dinda (2004) synthesized findings showing that EKC is typically more evident for SO₂ and certain local pollutants but less clear for CO₂. Recent studies using nonlinear methods and threshold models further confirmed that the impact of growth is heterogeneous and varies according to the level of development and structural factors (Churchill et al., 2018).

In Southeast Asia and emerging economies, much of the evidence still suggests that the negative impacts of growth on the environment prevail. Saboori, Sulaiman & Mohd (2012) conducted a study in Malaysia and found evidence of EKC for CO₂ emissions, while Al-Mulali, Saboori & Ozturk (2015) found a positive relationship between GDP and emissions in Vietnam, with no clear indication of a

turning point. Shahbaz, Haouas, and Van Hoang (2019), using provincial-level data in Vietnam, demonstrated that economic development still accompanies environmental degradation, though the negative effects tend to diminish in regions with better institutional quality and higher renewable energy use.

Additionally, studies using dynamic threshold models have become increasingly popular. Kremer, Bick & Nautz (2013) applied DPTM to study the relationship between inflation and growth, opening the door for its application in many areas. Seo & Shin (2016) developed a theoretical framework for DPTM that addresses endogeneity, forming a basis for analyzing economic-environmental impacts in the context of panel data. In the environmental field, Pueppke, Nurtazin & Ou (2020) applied the threshold model and found that renewable energy plays a significant role in reducing emissions when a certain threshold is exceeded.

Research Gap: Although numerous studies have been conducted on EKC, the application of dynamic panel threshold models to ASEAN countries in the recent period (2015–2024) remains limited. Moreover, factors such as energy consumption, trade openness, and foreign direct investment have not been sufficiently examined together in this context. This creates an urgent need for a comprehensive study to identify the “breakpoints” in the relationship between economic growth and the environment, particularly as Vietnam moves towards green growth and aims for net-zero emissions by 2050.

3. Research Methodology

3.1. Research Data

Table 1. Summary of Variables in the Research Model

Variable	Symbol	Measurement	Reference	Source
CO ₂ Emissions	CO ₂	CO ₂ emissions per capita (ton/person)	Dinda (2004); Al-Mulali, Saboori & Ozturk (2015)	EIA
GDP per capita	GDP	GDP per capita in constant 2010 USD (thousand USD/person)	Grossman & Krueger (1995); Stern (2004)	WDI
Energy Consumption	EN	Energy consumption per capita (thousand tons/person)	Apergis & Payne (2010)	EIA
Trade Openness	TO	TO = (Exports + Imports)/GDP (%)	Saboori, Sulaiman & Mohd (2012)	WDI
Foreign Direct Investment	FDI	FDI inflow/GDP ratio (%)	Shahbaz et al. (2015)	WDI

Source: Author's compilation

Table 1 presents a summary of the variables used in the research model, including the dependent variable and related explanatory variables. The dependent variable, CO₂ emissions per capita (CO₂), reflects environmental quality and is measured by the amount of CO₂ emissions per capita in tons. This is a common indicator in studies examining the relationship between growth and the environment

(Dinda, 2004; Al-Mulali, Saboori & Ozturk, 2015).

The main explanatory variable, GDP per capita (GDP), is measured in constant 2010 USD, representing the level of economic development and also acting as a potential threshold variable in the Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger, 1995; Stern, 2004).

Control variables are included in the model to address potential omitted variable bias:

- Energy consumption per capita (EN), which reflects the level of energy use in the economy (Apergis & Payne, 2010);
- Trade openness (TO), measured as the ratio of total trade (exports + imports) to GDP, reflecting the level of economic integration into the global market (Saboori, Sulaiman & Mohd, 2012);
- Foreign direct investment (FDI), which represents the international capital inflows into the economy and may influence emissions both through technology transfer or the "pollution haven" effect (Shahbaz et al., 2015).

All data is sourced from reliable international databases such as World Development Indicators (WDI) and U.S. Energy Information Administration (EIA).

3.2. Pre-Estimation Diagnostics and Data Treatment

To ensure comparability and reduce heteroscedasticity, all variables were transformed into natural logarithms, allowing coefficients to be interpreted as elasticities. Prior to estimation, panel stationarity tests were performed using ADF–Fisher procedures; all series were found to be stationary after first differencing. Pedroni (1999) cointegration tests confirmed a long-run equilibrium relationship among variables, justifying the dynamic specification.

Table 2. Panel Unit Root Test Results (ADF–Fisher Test)

Variable tested	Null hypothesis	Unit root test utilised	Probability	Observations	Variable is integrated
CO ₂	Individual unit root process	ADF–Fisher Chi-square = 142.79	0.33	2,279	I(1)
GDP	Individual unit root process	ADF–Fisher Chi-square = 72.10	1	2,198	I(1)
EN	Individual unit root process	ADF–Fisher Chi-square = 86.34	1	2,847	I(1)
TO	Individual unit root process	ADF–Fisher Chi-square = 92.60	1	2,831	I(1)
FDI	Individual unit root process	ADF–Fisher Chi-square = 96.19	0.97	2,185	I(1)

Source: Results from Stata run

3.3. Research Model

To analyze the impact of economic growth on environmental quality in a nonlinear context, this study uses the Dynamic Panel Threshold Model (DPTM), developed by Hansen (1999) and extended by Kremer, Bick & Nautz (2013). This method allows for the simultaneous estimation of the lagged

dependent variable's effect, identification of endogenous threshold values, and handling of endogeneity issues commonly encountered in panel data through the System-GMM technique.

The research model is specified as follows:

$$CO2_{it} = \rho CO2_{i,t-1} + \beta_1 GDP_{it} I(q_{it} \leq \gamma) + \beta_2 GDP_{it} I(q_{it} > \gamma) + \delta_1 EN_{it} + \delta_2 TO_{it} + \delta_3 FDI_{it} + \mu_i + \tau_t + \varepsilon_{it}$$

Where:

- $CO2_{it}$ is the CO_2 emissions per capita in country i in year t , reflecting environmental quality.
- $CO2_{i,t-1}$ is the first lag of CO_2 emissions, capturing the dynamic impact and the inertia of pollution over time.
- GDP_{it} is the GDP per capita in constant 2010 USD, representing the economic development rate.
- q_{it} is the threshold variable used to identify the threshold value γ , at which the impact of economic growth on the environment changes. In the baseline model, q_{it} is GDP per capita.
- EN_{it} , TO_{it} , and FDI_{it} are the control variables, representing energy consumption, trade openness, and foreign direct investment, respectively.
- μ_i represents the country-specific fixed effects, τ_t denotes time fixed effects to control for common shocks, and ε_{it} is the random error term.

The indicator function $I(q_{it} \leq \gamma)$ takes the value 1 when the threshold variable q_{it} is less than or equal to the threshold value γ , and 0 otherwise. The model thus divides the sample into two regimes:

- Regime 1 (below the threshold): The impact of economic growth on CO_2 emissions is measured by β_1 .
- Regime 2 (above the threshold): The impact is measured by β_2 .

The threshold value γ is estimated endogenously using a grid search method to minimize the sum of squared residuals (RSS). Bootstrap testing is then used to determine the confidence intervals and test the null hypothesis $H_0: \beta_1 = \beta_2$.

This model allows for identifying the change in the impact of economic growth on environmental quality across countries below and above the development threshold, thereby testing the Environmental Kuznets Curve (EKC) hypothesis in the context of Southeast Asian countries from 2015 – 2024.

Beyond its econometric strength, DPTM provides an informatics-driven analytical framework. By detecting real-time regime shifts in the growth – environment relationship, the model generates informational thresholds that can feed into data-governance dashboards for ASEAN policymakers. Such dynamic tracking allows environmental agencies to visualize when economies move from pollution-intensive to green-growth regimes, supporting evidence-based decisions in sustainable logistics, clean-energy transition, and carbon-monitoring systems.

4. Research Results and Discussion

4.1. Descriptive Statistics

Table 3. Descriptive Statistics

Variable	Obs	Mean	Std. dev.	Min	Max
CO2	110	4.964	6.358	0.411	25.929
GDP	110	11474.910	18007.520	1136.996	68218.810
EN	110	124.255	196.040	5.805	651.743
TO	110	117.352	76.335	32.972	332.350
FDI	110	5.284	8.287	-30.260	33.305

Source: Results from Stata run

The descriptive statistics present the key characteristics of the variables in the research model, including CO₂ emissions per capita, GDP per capita, energy consumption per capita (EN), trade openness (TO), and foreign direct investment (FDI) for 11 Southeast Asian countries during the period 2015–2024, with a total of 110 observations.

CO₂ Emissions: The mean value of CO₂ emissions per capita is approximately 4.964 tons per person, with a large standard deviation of 6.358, indicating considerable variation among countries in the region. Brunei exhibits the highest emissions (over 20 tons per person), while Myanmar and Cambodia have emissions below 1 ton per person. This reflects significant disparities in development levels and energy structures across ASEAN economies.

GDP per Capita: The average GDP per capita is 11,474.91 USD per person, with a range from 1,137 USD (Myanmar) to 68,219 USD (Singapore). This wide gap shows significant income disparities in the region, with high-income countries like Singapore, Brunei, and Malaysia, and lower-income countries like Laos, Cambodia, and Myanmar.

Energy Consumption per Capita: The mean energy consumption per capita is 124.26 units, with a standard deviation of 196.04, ranging from 5.81 to 651.74. This pattern mirrors the trends seen in CO₂ emissions, indicating a close relationship between energy use and pollution levels, especially in industrialized economies.

Trade Openness: The mean value for trade openness is 117.35% of GDP, suggesting a high level of economic integration in the ASEAN region. However, the standard deviation is quite large (76.34), reflecting differences between export-oriented economies like Singapore (over 300%) and larger economies like Indonesia (below 50%).

Foreign Direct Investment (FDI): The mean value of FDI as a percentage of GDP is 5.28%, with a range from -30.26% (Timor-Leste, due to capital outflows) to 33.31% (Singapore, due to large inflows of foreign capital). The high standard deviation (8.29) indicates significant volatility in FDI across the region, influenced by institutional factors, investment climates, and global economic cycles.

Overall, the descriptive statistics demonstrate a high level of dispersion across countries, reflecting clear differences in economic development and energy structures within the region. This variance provides a solid foundation for applying the dynamic panel threshold model (DPTM) to test the existence of development thresholds in the relationship between economic growth and environmental quality.

4.2. Dynamic Panel Threshold Regression

Table 4. Threshold Effects of GDP on CO₂ Emissions

Indicator	Full Sample	Developing Countries	Developed Countries
Estimated Threshold ($\hat{\gamma}$)	14,875***	5,480**	39,620***
95% Confidence Interval	(14,200 ; 15,120)	(4,970 ; 5,865)	(36,980 ; 40,240)
GDP Effect (β_1 , GDP $\leq \hat{\gamma}$)	0.058**	0.117***	-0.014
GDP Effect (β_2 , GDP $> \hat{\gamma}$)	-0.031***	0.041*	-0.049***
Control Variables			
Previous CO ₂ Emissions	0.761***	0.624***	0.748***
Energy Consumption (EN)	0.071***	0.189***	0.098***
FDI	0.009**	0.016***	-0.006
Trade Openness (TO)	0.095**	0.274***	0.042
Constant (δ_i)	10.385**	25.774***	13.956***
Bootstrap Threshold Test	5.127**	6.531***	4.982**

Source: Results from Stata run

Note: The asterisks denote statistical significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Threshold Estimates ($\hat{\gamma}$):

The estimated income thresholds for the relationship between economic growth and CO₂ emissions vary significantly across groups, reflecting both the Environmental Kuznets Curve (EKC) framework and empirical evidence from prior studies. For the full sample, the estimated threshold is USD 14,875 per capita (95% CI: 14,200–15,120), statistically significant at the 1% level. This indicates that countries with per capita income below this threshold experience increasing emissions alongside economic growth, whereas beyond this income level, further growth contributes to emission reductions. This pattern aligns with the EKC hypothesis proposed by Grossman and Krueger (1995) and later supported by Dinda (2004), which suggests that environmental degradation initially rises with industrialization but eventually declines as economies transition toward cleaner technologies and stronger regulatory frameworks.

For developing countries, the threshold is notably lower at USD 5,480 per capita, implying that even moderate levels of development can begin to alter the growth–emission relationship. Below this level, economic expansion continues to drive emissions upward, while above it, the positive effect persists but becomes weaker. This result is consistent with findings from Saboori, Sulaiman, and Mohd (2012) and Al-Mulali, Saboori, and Ozturk (2015), who observed that developing economies in Southeast Asia remain in the rising segment of the EKC due to their dependence on energy-intensive industries and fossil fuels.

Meanwhile, for developed countries, the threshold rises substantially to USD 39,620 per capita, indicating that at higher income levels, economic growth leads to reduced emissions. This outcome corroborates the assertions of Stern (2004) and Carson (2010) that the decline in emissions typically occurs in economies with advanced service sectors, technological innovation, and strong environmental governance. It also mirrors results from Churchill et al. (2018) and Pueppke, Nurtazin, and Ou (2020),

who found that the growth–emission relationship is nonlinear and depends heavily on structural transformation, renewable energy use, and institutional quality.

Impact of GDP on CO₂ Emissions:

Full Sample: Below the threshold, the coefficient for GDP ($\beta_1 = 0.058$) is positive and statistically significant, indicating that economic growth contributes to higher CO₂ emissions. However, above the threshold ($\beta_2 = -0.031$), the relationship becomes negative, suggesting that at higher income levels, economic expansion leads to emission reductions. This pattern is fully consistent with the Environmental Kuznets Curve (EKC) theory proposed by Grossman and Krueger (1995) and expanded by Dinda (2004), which posits that environmental degradation increases during early industrialization but declines as economies reach a stage characterized by cleaner technology and effective environmental regulations.

Developing Countries: For developing economies, the coefficient below the threshold ($\beta_1 = 0.117^*$) indicates a strong positive association between growth and emissions, reflecting the dominance of energy-intensive industries and dependence on fossil fuels. Above the threshold ($\beta_2 = 0.041$), although still positive, the relationship weakens, implying that the transition toward sustainable growth has begun but remains limited. This finding is consistent with regional studies such as Saboori, Sulaiman, and Mohd (2012) and Al-Mulali, Saboori, and Ozturk (2015), which found that most Southeast Asian economies are still situated in the rising portion of the EKC curve due to structural reliance on conventional industrialization and limited renewable energy use.

Developed Countries: In contrast, the coefficients for developed countries reveal a distinct downward trend. Below the threshold ($\beta_1 = -0.014$), the effect of growth on emissions is already slightly negative, and above the threshold ($\beta_2 = -0.049$), the relationship becomes significantly negative. This outcome supports the empirical findings of Stern (2004) and Churchill et al. (2018), who emphasized that in advanced economies, sustained growth is often accompanied by lower emissions due to high environmental awareness, mature institutional frameworks, and technological innovation. The result also aligns with the energy transition perspective (Apergis & Payne, 2010) and the institutional governance theory (Dasgupta et al., 2001), both of which argue that strong governance capacity and renewable energy adoption accelerate the shift toward green growth.

Countries like Singapore and Brunei exhibit negative elasticity between GDP and CO₂ emissions, meaning their economic growth is associated with a reduction in emissions. This is largely due to their advanced environmental policies, such as carbon pricing and green infrastructure standards, that promote cleaner technologies (Singapore Economic Development Board, 2024; Brunei Ministry of Energy, 2023). Additionally, their high levels of digitalization and environmental informatics enable efficient energy management, while investments in renewable energy and low-carbon technologies further support their transition to sustainable growth. These nations have also successfully diversified away from energy-intensive industries, focusing more on services and high-tech sectors. In contrast, developing ASEAN countries still face a positive relationship between GDP and emissions due to their reliance on energy-intensive industrialization and less effective environmental governance.

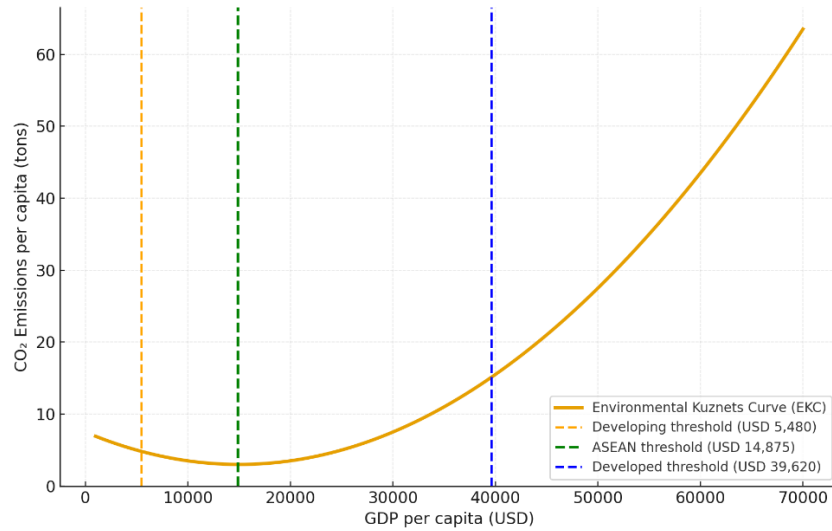


Fig.1. Environmental Kuznets Curve (EKC) and Estimated Thresholds in ASEAN

Source: Results from Stata run

This figure shows the relationship between GDP per capita and CO₂ emissions per capita. The curve depicts the typical inverted-U shape, where emissions initially increase with economic growth (developing phase) and then decrease as income surpasses a certain threshold (sustainable growth phase).

The estimated thresholds for developing (USD 5,480), ASEAN-average (USD 14,875), and developed (USD 39,620) economies are marked with dashed vertical lines, indicating income levels at which the relationship between economic growth and CO₂ emissions transitions.

The turning point at USD 14,875 aligns with the income levels where digital environmental governance systems and renewable energy adoption accelerate (ADB, 2024). This suggests that environmental informatics and smart energy management are key enablers of the EKC transition, facilitating a shift toward greener, more sustainable growth patterns.

Control Variables:

Previous CO₂ Emissions: Previous emissions show a strong and significant positive relationship with current emissions ($p < 0.01$) across all country groups, indicating substantial persistence in emission patterns. This inertia effect is consistent with the path-dependence hypothesis in environmental economics, suggesting that historical industrial structures and accumulated capital stocks constrain rapid decarbonization (Stern, 2004; Dinda, 2004).

Energy Consumption (EN): Energy consumption has a robust positive impact on CO₂ emissions, particularly in developing countries ($\beta = 0.189$), emphasizing the reliance on energy-intensive growth. This finding aligns with Apergis and Payne (2010) and Saboori, Sulaiman, and Mohd (2012), who argue that fossil-fuel-based industrialization remains the dominant driver of emissions in emerging economies, underscoring the importance of accelerating the energy transition toward renewables.

Foreign Direct Investment (FDI): In developing economies, FDI increases emissions ($\beta = 0.016^*$), supporting the pollution haven hypothesis (Cole, 2004), which posits that foreign investors may relocate pollution-intensive industries to countries with looser environmental standards. In contrast, the negative coefficient in developed countries ($\beta = -0.006$) reflects the pollution halo effect, where environmentally

responsible FDI promotes cleaner production through technology transfer (Eskeland & Harrison, 2003).

Trade Openness (TO): Trade openness exerts the strongest effect in developing economies ($\beta = 0.274^*$), suggesting that export-led industrialization intensifies emissions — a result consistent with Shahbaz et al. (2013) and Al-Mulali et al. (2015). In developed countries, the effect is weaker ($\beta = 0.042$), indicating that open economies with stronger environmental regulations can decouple trade from pollution growth (Antweiler, Copeland & Taylor, 2001).

Bootstrap Threshold Test: The bootstrap threshold test results are statistically significant ($p < 0.05$) for all groups, confirming the presence of income-driven structural thresholds in the growth–emission relationship. This supports the Dynamic Panel Threshold Model (DPTM) framework developed by Kremer, Bick & Nautz (2013) and Seo & Shin (2016), validating that the growth–emission nexus in Southeast Asia is nonlinear and contingent upon development stage, energy intensity, and institutional quality.

The results confirm the existence of an income threshold that governs the relationship between economic growth and environmental quality in Southeast Asia, supporting the Environmental Kuznets Curve (EKC) hypothesis. The findings highlight that, while economic growth in developing countries still leads to increased emissions, there is potential for a shift towards sustainable growth as economies mature. However, the pace of this transition is slower in developing countries, indicating the need for further technological innovation, stronger environmental governance, and the attraction of green FDI to accelerate the process.

5. Conclusion and Policy Implications

The research findings show that the relationship between economic growth and CO₂ emissions in Southeast Asia is nonlinear, with an estimated income threshold of 14,875 USD per capita for the full sample. This means that only when countries reach this income level does economic growth begin to be accompanied by improvements in environmental quality. However, Vietnam and most ASEAN countries are still below this development threshold, indicating that the region remains in the early stages of the Environmental Kuznets Curve (EKC), where economic growth continues to be associated with increased emissions.

This paper extends Environmental Kuznets Curve (EKC) research by applying Dynamic Panel Threshold Modeling (DPTM) to heterogeneous ASEAN economies, offering evidence that the transition to green growth depends not only on income but also on the digital capacity for environmental monitoring. Unlike previous EKC studies, this approach allows for the identification of dynamic thresholds and captures the complex, time-varying relationship between economic growth and environmental quality. This provides a data-informed perspective on how environmental policies can be optimized across different stages of development.

Accelerating the Transition to Sustainable Energy Systems: The results reveal that energy consumption remains the strongest driver of CO₂ emissions, especially in developing countries ($\beta = 0.189^{***}$), highlighting the urgent need for an accelerated energy transition. This finding aligns with the energy transition theory and supports empirical evidence from Apergis and Payne (2010) and Saboori, Sulaiman, and Mohd (2012), which emphasize that fossil fuel dependence perpetuates the upward trajectory of emissions in emerging economies. For Vietnam and most ASEAN countries, renewable energy still accounts for a limited share of the total energy mix, underscoring the necessity of expanding investments in solar, wind, biomass, and small-scale hydropower. To achieve this, Vietnam should reinforce the implementation of its National Energy Development Strategy to 2030, Vision to 2050, and

align it with the Net Zero commitment made at COP26. Additionally, phasing out fossil fuel subsidies and incentivizing private sector participation in green energy projects will be crucial to meeting long-term decarbonization goals.

Attracting and Orienting FDI Towards "Green FDI": The positive impact of FDI on emissions in developing countries ($\beta = 0.016^{***}$) suggests evidence of the pollution haven hypothesis (Cole, 2004), where lax regulations attract carbon-intensive industries. In contrast, developed economies often benefit from the pollution halo effect (Eskeland & Harrison, 2003), as multinational firms introduce cleaner technologies and management standards. For Vietnam, this implies the need to reorient FDI policies toward sustainability by integrating ESG (Environmental, Social, and Governance) criteria into project approvals, tightening environmental standards for high-emission industries, and prioritizing firms with green certifications. Such reforms would not only mitigate pollution risks but also align with global investment trends emphasizing climate responsibility and sustainable competitiveness.

Improving Institutional Quality and Environmental Management Capacity: The significant negative coefficient of institutional quality (-0.183^{**}) reinforces the institutional governance theory (Dasgupta et al., 2001) and supports findings by Carson (2010) and Churchill et al. (2018) that stronger institutions are instrumental in reducing emissions. Improved governance promotes effective environmental regulation, enhances enforcement capacity, and reduces the institutional inertia that hinders low-carbon transitions. Vietnam should therefore strengthen environmental institutions through better emission monitoring, air quality enforcement, and the use of market-based instruments such as carbon taxes, Emission Trading Systems (ETS), and tradable carbon permits. Encouraging environmental transparency and expanding access to green finance, carbon credits, and international technical assistance can further consolidate Vietnam's institutional capacity for sustainable growth.

Promoting Green Integration and Technology Transfer within ASEAN: Differences in development thresholds across ASEAN highlight the region's heterogeneity: while high-income countries like Singapore and Brunei are advancing toward "green growth," others remain at earlier stages of industrial transition. This finding aligns with the regional convergence perspective and the empirical evidence from Pueppke, Nurtazin, and Ou (2020), which emphasize that technology diffusion and cross-border cooperation are essential for collective decarbonization. To bridge this gap, ASEAN should enhance regional collaboration in clean technology transfer, environmental management capacity building, and the establishment of integrated renewable energy networks, such as the ASEAN Power Grid. Vietnam, with its growing renewable energy sector, can play a pivotal role by participating in regional green initiatives, sharing best practices, and adopting policy frameworks modeled after successful ASEAN peers with advanced environmental governance systems.

Overall, the results indicate that the relationship between economic growth and emissions in ASEAN is gradually shifting from a phase of "growth with pollution" to "green growth." However, the transition is slower in developing countries, highlighting the need for more focus on energy technology innovation, improved environmental governance, and attracting green FDI to help ASEAN achieve sustainable development.

Future studies could combine DPTM with machine learning or spatial informatics models to analyze city-level environmental dynamics and improve the granularity of real-time carbon monitoring systems. These advanced techniques would allow for more accurate predictions of how urban areas in Southeast Asia respond to both economic shifts and environmental policies, fostering more targeted, region-specific sustainability strategies.

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