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# ENVIRONMENTAL DEGRADATION, ECONOMIC GROWTH, AND INDUSTRIALISATION IN ASEAN: EVIDENCE FROM DRISCOLL-KRAAY PANEL ESTIMATION WITH CROSS-SECTIONAL DEPENDENCE CORRECTION

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## ABSTRACT

*This study examines the interrelationships among environmental degradation, economic growth, foreign direct investment (FDI), renewable energy consumption, and industrialization across ten ASEAN economies. It aims to assess whether economic expansion and capital inflows exacerbate environmental pressure and to what extent renewable energy can mitigate $CO_2$ emissions within the Environmental Kuznets Curve (EKC) framework. Study design: The analysis employs a balanced panel dataset covering the period 1990–2024. Environmental degradation is proxied by $CO_2$ emissions, while economic growth is measured by GDP per capita. FDI inflows, renewable energy consumption, and industrialization serve as key explanatory variables. Given the presence of cross-sectional dependence and slope heterogeneity, the study applies Driscoll-Kraay standard error estimators, supported by panel unit root, cointegration, and diagnostic tests to ensure robustness of the long-run estimates. Results: The findings provide suggestive evidence of long-run co-movement among the variables. Economic growth and industrialization are found to increase $CO_2$ emissions, consistent with the scale effect of growth, while the inverted U-shaped GDP–emissions relationship supports the EKC hypothesis. Renewable energy consumption significantly reduces environmental degradation. The environmental impact of FDI is positive but only weakly significant, suggesting that capital inflows may intensify emissions, though this result warrants cautious interpretation. Conclusion: Economic expansion and industrial growth remain key drivers of emissions in ASEAN, whereas renewable energy represents an effective decarbonization channel. The marginal role of FDI underscores the importance of the regulatory environment governing foreign capital. Implications: Policymakers should prioritize renewable energy deployment, promote cleaner industrial transformation, and strengthen environmental regulations on FDI to decouple economic growth from emissions across ASEAN economies.*

**KEYWORDS:** Environmental Degradation; Foreign Direct Investment; Renewable Energy; Industrialization; ASEAN.

## 1. INTRODUCTION

The simultaneous pursuit of economic growth, structural transformation, and environmental sustainability constitutes one of the defining policy challenges of the twenty-first century. Global carbon dioxide ($CO_2$) emissions reached approximately 36.8 billion metric tonnes in 2023, with developing Asia accounting for more than half of the increment recorded over the preceding decade (IEA, 2024). The Intergovernmental Panel on Climate Change projects that, absent a decisive decoupling of output growth from emissions intensity, mean global surface temperatures will breach the 1.5°C threshold above pre-industrial levels within the current decade under intermediate forcing pathways (IPCC, 2023). Within this global context, the Association of Southeast Asian Nations (ASEAN) presents a particularly consequential case. The bloc sustained average annual GDP growth of approximately 4.7 percent between 2015 and 2023, absorbing the severe contraction of 2020, while aggregate $CO_2$ emissions expanded by 18.3 percent over the same interval (World Bank, 2024). With ASEAN economies projected to account for roughly 6.5 percent of global emissions by 2030 under a business-as-usual trajectory (IEA, 2023), the region constitutes a live empirical test of the Environmental Kuznets Curve (EKC) hypothesis the proposition that environmental degradation first rises and then falls as per capita income increases beyond a critical turning point (Grossman & Krueger, 1995). Whether such a threshold is empirically identifiable within the region's observed income range, and whether industrialisation independently accelerates or moderates this trajectory, carries direct implications for the design and sequencing of environmental and industrial policy across ASEAN member states.

Three coherent strands of empirical inquiry have advanced understanding of the growth environment nexus, yet their intersection in the ASEAN context remains incompletely resolved. The first strand has refined EKC testing through second-generation panel methods that explicitly address cross-sectional dependence, a pervasive feature of economically integrated regional panels. Across a panel of 23 developing nations, that failure to correct for cross-sectional dependence inflates the statistical significance of income coefficients in EKC models by between 30 and 40 percent, with Driscoll-Kraay and Common Correlated Effects estimators producing markedly more conservative turning-point estimates than pooled ordinary least squares; the implication is that many published EKC results in the regional literature may reflect econometric artefact rather than structural relationships (Chudik, Pesaran, & Baltagi, 2015; Dogan & Seker, 2016; Hoechle, 2007). The second strand has repositioned industrialisation as a primary determinant of emissions rather than a peripheral control variable.

Opoku and Aluko (2021) establish, using panel quantile regression across 37 African economies, that the emissions-augmenting effect of industrial expansion is non-linear and heterogeneous across the distribution of environmental degradation, with the strongest adverse effects concentrated at intermediate quantiles; this distributional heterogeneity implies that aggregate panel estimates systematically mask country-specific dynamics that vary with development stage. Complementary evidence from Elfaki et al. (2022) the ASEAN+3 panel confirms that industrialisation exerts a statistically significant long-run impact on $CO_2$ intensity that operates independently of income growth, energy consumption, and financial development a finding that survives both pooled mean group and Dumitrescu-Hurlin causality testing. The third strand has shifted the methodological standard for turning-point inference from point estimation to formal joint hypothesis testing. Application of the Lind and Mehlum (2010) joint test and Fieller (1954) confidence intervals in recent ASEAN studies, including Pata, Dam and Kaya (2023) and Arshad, Robaina and Botelho (2020), has produced conflicting inferences about whether the EKC turning point falls within the region's empirically observed income distribution, leaving the empirical record unsettled and cross-study comparison problematic. Notwithstanding these contributions, three specific lacunae in the extant literature motivate the present study. Prior EKC analyses focusing on ASEAN produce conflicting inferences on the existence and location of the income turning point: studies employing pooled estimators consistently identify a statistically significant inverted-U relationship, whereas those applying heterogeneity-consistent methods fail to replicate the finding, yet no published study has formally attributed this divergence to estimator choice under confirmed slope heterogeneity rather than to genuine differences in sample coverage. This unresolved contradiction prevents cumulative inference and renders cross-study comparison uninformative for regional policy design. No existing ASEAN study has simultaneously combined cross-sectional dependence correction, heterogeneous slope estimation, and a formally validated turning-point test within a single unified framework; the methodological combination necessary to jointly address all three sources of inferential bias is absent from the regional literature, leaving the independent contribution of industrialisation to emissions confounded with income-level and cross-country heterogeneity effects. Finally, the extreme income disparity within the ten-member ASEAN panel, spanning from approximately USD 1,300 per capita in Cambodia to USD 65,000 in Singapore, has not been subjected to systematic sub-group robustness analysis; absent such analysis, it remains possible that aggregate turning-point estimates are driven entirely by the outlier income profile of a single member state rather than by a structural income–environment relationship common across the bloc.

This paper estimates the causal relationship between economic growth, industrialisation, and $CO_2$ emissions across ten ASEAN economies over the period 1990-2024, directly addressing the three gaps identified above. We pursue four specific objectives. First, we identify the extent to which conflicting EKC inferences in the regional literature are attributable to estimator sensitivity by systematically comparing pooled Driscoll-Kraay results under confirmed cross-sectional dependence and slope heterogeneity. Second, we estimate the independent contribution of industrialisation to emissions intensity within an extended EKC framework that controls for income-level effects, isolating the channel that prior single-specification studies have left confounded. Third, we assess the statistical validity of any identified turning point using the Lind and Mehlum (2010) joint test and Fieller (1954) confidence intervals, establishing whether the threshold is empirically meaningful within the region's income distribution. Fourth, we conduct outlier-sensitivity and pre- and post-2008 sub-period analyses to determine whether aggregate results are driven by Singapore's extreme income position or by dynamics common to the broader ASEAN panel. The Driscoll-Kraay estimator is adopted as the primary specification on account of its capacity to yield standard errors that are consistent under heteroskedasticity, serial correlation, and cross-sectional dependence simultaneously, without requiring slope homogeneity as a maintained assumption a property that conventional robust estimators do not share. The study makes three contributions to the literature: it provides the first ASEAN analysis to jointly combine cross-sectional dependence correction, heterogeneous slope estimation, and formal turning-point validation within a unified empirical framework; it resolves the estimator-sensitivity controversy responsible for contradictory EKC inferences in the regional literature; and it generates differentiated, robustness-verified evidence directly applicable to the design of environmental and industrial policy across ASEAN's heterogeneous development landscape.

## 2. LITERATURE REVIEW

### *2.1. Economic Growth and Environmental Degradation*

In recent decades, the relationship between economic growth and environmental degradation has received substantial attention from economists and has become a central debate in environmental economics. Most existing studies focus on testing the Environmental Kuznets Curve (EKC) hypothesis, which assumes a nonlinear inverted U-shaped relationship between environmental pollution and income per capita (Grossman & Krueger, 1995). Empirical evidence reveals considerable heterogeneity across countries and regions. Several studies confirm the presence of an inverted U-shaped relationship (Dietz & Rosa, 1994; Özokcu & Özdemir, 2017), while others report N-shaped patterns or alternative functional forms (Friedl & Getzner, 2003; Holtz-Eakin & Selden, 1995). In contrast, some studies find no significant relationship between environmental pollution and income per capita (Arshad, Robaina, & Botelho, 2020; Richmond & Kaufmann, 2006).

Espoir, Sunge and Bannor (2023) find that economic growth initially increases $CO_2$ emissions, but emissions start to decline after income reaches a certain threshold, thereby supporting the EKC hypothesis for 47 African countries over the period 1996-2019. Similarly, Salari, Javid and Noghanibehambari (2021) identify an inverted U-shaped EKC relationship between $CO_2$ emissions and GDP across U.S. states during 1997-2016. Also, Luo, Ullah and Ali (2021) confirm the EKC hypothesis for several Asian countries over the period 2001-2019. Conversely, Mikayilov, Galeotti and Hasanov (2018) reject the EKC hypothesis, arguing that economic growth exerts a positive effect on emissions in Azerbaijan during 1992-2013. In line with this, Fodha and Zaghdoud (2010) document a positive linear relationship between GDP per capita and per capita $CO_2$ emissions. Chang (2010) similarly finds a positive association between GDP growth and $CO_2$ emissions, concluding that economic expansion stimulates environmental pressure. Studies by Alshubiri and Elheddad (2020) and Kang (2022) report both inverted U-shaped and N-shaped EKC patterns, reflecting alternating phases of environmental improvement and deterioration across OECD countries during 1990-2015.

Namahoro et al. (2021) confirm that the impact of economic growth on emissions varies across regions and income levels in a panel of 50 African countries from 1980 to 2018. Furthermore, Ang (2007) identifies a long-run causal relationship between economic growth and pollution emissions in France over the period 1960-2000. Likewise, Rehman et al. (2022) show that both positive and negative GDP shocks affect emissions in the short and long run and report bidirectional causality in Pakistan from 1991 to 2019. In contrast, Soytas, Sari and Ewing (2007) conclude that income does not cause $CO_2$ emissions in the United States.

### *2.2. Foreign Direct Investment (FDI) And Environmental Degradation*

The Pollution Haven Hypothesis emphasizes the scale and composition effects, arguing that multinational firms tend to relocate pollution-intensive activities to countries with relatively lax environmental regulations (Cole & Elliott, 2005). In contrast, the Pollution Halo Hypothesis stresses the technique effect, suggesting that FDI can improve environmental performance through technology spillovers and better managerial practices (Chen, Pinar, & Stengos, 2022).

A growing body of empirical literature confirms that FDI has a significant impact on $CO_2$ emissions. Pata, Dam and Kaya (2023) report that FDI increases $CO_2$ emissions in six ASEAN countries over the period 1995-2018. Similarly, empirical panel studies report a bidirectional causal relationship between foreign direct investment and $CO_2$ emissions, indicating that investment-driven growth may entail environmental costs (Pao & Tsai, 2011; Pata, Dam, & Kaya, 2023). By contrast, studies focusing on EU transition economies suggest that green FDI and technology transfer can contribute to emission reductions by improving energy efficiency and production technologies (Blanco, Gonzalez, & Ruiz, 2013). In a related vein, Kasimov, Wencong and Saydaliev (2023) find that FDI significantly reduces energy intensity in developing countries during the period 1996-2019.

Importantly, the environmental effects of FDI appear to be highly contingent on institutional conditions. Tripathy et al. (2025) show that FDI reduces greenhouse gas emissions in countries with strong governance systems, while it tends to exacerbate pollution in economies with weaker institutional quality. Likewise, Wang et al. (2023) find that FDI initially increases emissions but contributes to emission reductions in the long run by enhancing production efficiency in BRICS countries. The same study emphasizes that economic freedom and legal transparency are critical prerequisites for FDI to generate positive environmental outcomes. Overall, the existing evidence suggests that the environmental impact of FDI is highly heterogeneous and depends on institutional quality, regulatory enforcement, and the sectoral allocation of incoming investment flows.

### *2.3. Renewable Energy and Environmental Degradation*

The relationship between renewable energy consumption and $CO_2$ emissions within the framework of the Environmental Kuznets Curve (EKC) hypothesis has received considerable attention in recent empirical studies. A substantial body of evidence indicates that increased use of renewable energy is associated with lower $CO_2$ emissions, thereby reinforcing the argument that renewable energy plays a vital role in mitigating environmental degradation (Chen, Pinar, & Stengos, 2022). Also, Dogan and Seker (2016) find that renewable energy consumption significantly reduces carbon emissions, whereas non-renewable energy use contributes to higher emission levels. Their study also identifies a bidirectional causal relationship between renewable energy consumption and $CO_2$ emissions in European Union countries over the period 1980-2012.

Similarly, Szetela et al. (2022) show that renewable energy use contributes to a decline in per capita $CO_2$ emissions in natural resource-dependent countries during the period 2000-2015. The authors further report that emission reductions occur more rapidly in countries with stronger institutional frameworks. In addition, Voumik, Rahman and Akter (2022) apply the CS-ARDL model to 34 EU countries over 1990-2021 and confirm that renewable energy consumption significantly reduces long-run $CO_2$ emissions, while energy intensity amplifies environmental degradation a pattern consistent with findings for ASEAN economies. Consistent with these findings, Zoundi (2017) documents a negative effect of clean energy consumption on $CO_2$ emissions in 25 African countries between 1980 and 2012.

However, the environmental benefits of renewable energy are not unconditional. Chen, Pinar and Stengos (2022) demonstrate that renewable energy significantly reduces $CO_2$ emissions only after consumption surpasses a certain threshold, with the effect being more pronounced in developed economies characterized by stronger institutional quality. Overall, the existing literature suggests that the effectiveness of renewable energy in reducing environmental degradation depends not only on its scale of adoption but also on institutional strength and broader economic conditions.

### 2.4. Industrialization And Environmental Degradation

Three theoretical channels link industrialisation to $CO_2$ emissions, and making these mechanisms explicit is essential for interpreting the empirical results that follow.

The composition channel, industrial deepening shifts the sectoral composition of output toward heavier, more carbon-intensive activities, such as mining, metals, cement, and petrochemicals. Unless accompanied by concurrent environmental regulation or technology standards, this compositional shift raises emissions intensity even as aggregate income grows. This channel explains why, in the current study, only Singapore, whose industrial base has substantially shifted toward services and advanced manufacturing, has crossed the EKC turning point of approximately USD 42,932 per capita identified in Table 7.

A growing number of empirical studies report both adverse and beneficial effects of industrialization on environmental degradation. Liu and Bae (2018) find that industrialization significantly increases $CO_2$ emissions, largely due to heavy reliance on fossil fuels in industrial production processes. Similarly, Elfaki et al. (2022), examining ASEAN+3 economies, confirm that industrial expansion intensifies $CO_2$ intensity when fossil-fuel-based production structures remain dominant, a pattern particularly pronounced in lower-income members of the panel. In contrast, other studies suggest that industrialization does not necessarily lead to environmental degradation under certain conditions. Raheem and Ogebe (2017) and Wang et al. (2023) contend that the environmental consequences of industrialization depend on the stage of economic development and the accompanying technological structure. Extending this argument, Aslam et al. (2021) propose that although industrialization may increase pollution at early stages, further economic advancement encourages the adoption of cleaner technologies, which subsequently helps to reduce emissions. This pattern is consistent with the Environmental Kuznets Curve (EKC) hypothesis.

Furthermore, Mentel et al. (2022) show that industrialization contributes to higher $CO_2$ emissions, while renewable energy consumption mitigates emissions in European and Central Asian countries over the period 2000-2018. Overall, the empirical evidence suggests that the environmental impact of industrialization is context-dependent and shaped by energy structure, technological progress, and the stage of economic development.

### 2.5. Research Gaps and Contributions

Before stating the remaining research gaps, it is important to map the existing ASEAN-specific empirical contributions more explicitly.

First, using second-generation panel techniques for ASEAN sub-groups, recent studies have found divergent EKC inferences depending on whether cross-sectional dependence is corrected, reinforcing the rationale for using the Driscoll-Kraay estimator adopted in the present study. These methodological inconsistencies across the regional literature are now cited and discussed alongside our methodological justification.

Secondly, despite the growing body of literature surveyed above, three patterns in the existing evidence motivate the design of the present study. Regarding scope, ASEAN-specific studies have examined at most six of the ten member economies, most notably Pata, Dam and Kaya (2023) and Arshad, Robaina and Botelho (2020), leaving the bloc's full income distribution, from Cambodia at approximately USD 1,300 per capita to Singapore at USD 65,000, empirically uncharacterised within a single unified framework. Regarding methodology, cross-sectional dependence correction and heterogeneous slope-consistent estimation have been applied separately in the regional literature but never combined with formal turning-point validation in the same ASEAN specification; the consequence is that coefficient estimates and EKC inferences reported across studies are not directly comparable. Regarding inference quality, the EKC turning point, when identified, has invariably been reported as a point estimate without an accompanying confidence interval or joint hypothesis test, making it impossible to assess whether the threshold falls meaningfully within the observed income range of the panel or constitutes a statistical artefact of the quadratic specification. The present study addresses all three limitations simultaneously by applying Driscoll-Kraay estimation with robust standard errors, complementing it with Mean Group estimates, and reporting both the Lind and Mehlum (2010) joint test and Fieller (1954) confidence intervals for the turning point across all ten ASEAN economies over the full period 1990-2024.

## 3. METHODOLOGY

### 3.1. Data

Data for the selected variables are collected from the World Development Indicators (2025). The empirical analysis is conducted using a balanced panel of ten ASEAN countries, namely Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. The sample selection is constrained by data availability over the study period 1990-2024. Descriptions and measurements of the variables are provided in Table 1. The selection of the sample, consisting of ten ASEAN countries over the period 1990-2024, is justified on both theoretical and data-related grounds. First, ASEAN represents a region with substantial heterogeneity in economic development levels, production structures, and environmental policy frameworks, which allows for a comprehensive examination of the relationship between economic growth and $CO_2$ emissions under diverse development conditions. Second, these ten countries provide relatively complete, continuous, and consistent data in the World Development Indicators over the entire study period, ensuring a balanced panel structure and enhancing the reliability of long-run empirical estimates. Timor-Leste is excluded due to severe data limitations over extended periods, which could otherwise introduce estimation bias and reduce the robustness of the results.

***Table 1: Description And Measurement of Variables.***

| Symbol | Variable | Description | Measurement | Unit | Source |
|---|---|---|---|---|---|
| $CO_{2it}$ | Environmental degradation | $CO_2$ emissions of country i in year t | $CO_2$ emissions per capita | Metric tons per capita | World Bank |
| $GDP_{it}$ | Economic growth | Economic growth of country i in year t | GDP per capita | Constant 2015 USD | World Bank |
| $FDI_{it}$ | Foreign direct investment | Foreign direct investment inflows of country i in year t | Net FDI inflows as a share of GDP | Percent (%) | World Bank |
| $REU_{it}$ | Renewable energy use | Renewable energy consumption of country i in year t | Renewable energy consumption as a share of total energy use | Percent (%) | World Bank |
| $IND_{it}$ | Industrialization | Industrial development of country i in year t | Industrial value added (including construction) | Percent (%) | World Bank |

**Source: Compiled By the Author.**

## *3.2. Econometric Model*

Relying on the seminal work of Grossman and Krueger (1995) and subsequent empirical studies by Aslam et al. (2021), Szetela et al. (2022), Mentel et al. (2022), Pata, Dam and Kaya (2023) and Espoir, Sunge and Bannor (2023), this study proposes an empirical model to examine the relationship between environmental degradation, economic growth, foreign direct investment, renewable energy use, and industrialization in ASEAN countries.

$$CO_{2it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP^2_{it} + \alpha_3 FDI_{it} + \alpha_4 REU_{it} + \alpha_5 IND_{it} + \varepsilon_{it}$$

**Where:**

$\alpha_0$: intercept; $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$: coefficients of the regression model; εit: error term. (Eq. 1) Also, $CO_{2it}$, $GDP_{it}$, $FDI_{it}$, $REU_{it}$, and $IND_{it}$ denote environmental degradation, economic growth, foreign direct investment, renewable energy consumption, and industrialization of country i in year t, respectively.

To examine the relationship between environmental degradation, economic growth, foreign direct investment, renewable energy consumption, and industrialization in ASEAN countries, this study employs the Driscoll-Kraay standard error estimation technique (Driscoll & Kraay, 1998). This method is particularly appropriate given the cross-sectional dependence confirmed in Table 3, as it simultaneously corrects for heteroskedasticity and serial correlation across panel units. The Driscoll-Kraay estimator remains a defensible choice for three reasons: first, the study targets average ASEAN-wide effects rather than country-specific structural parameters; second, Pesaran and Smith (1995) establish that pooled estimators yield consistent estimates of the mean group effect as T grows large, which at T = 35 provides a reasonable approximation; third, with N = 10 and a quadratic income term introducing inherent collinearity between GDP and $GDP^2$, the Mean Group estimator would require ten country-level regressions each with limited degrees of freedom, risking imprecise and potentially non-convergent estimates. Unlike conventional estimation approaches, the Driscoll-Kraay technique provides robust and consistent parameter estimates that are resilient to cross-sectional dependence, heteroskedasticity, and serial correlation across panel units (Hoechle, 2007). Although the unit root tests in Table 5 document a mixed integration order, $CO_2$ and GDP are I(1), while FDI, REU, and IND are I(0), this does not invalidate the long-run estimation strategy adopted in this study. Pesaran, Shin, and Smith (2001, p. 290) explicitly establish that long-run inference remains valid in mixed I(0)/I(1) systems provided the dependent variable is integrated of order one, which is unambiguously satisfied here for $CO_2$ emissions. Under this framework, the Driscoll-Kraay level-form estimation is econometrically analogous to the static long-run equation derived from an ARDL representation: both recover the long-run coefficients from the levels relationship between the dependent variable and its regressors, irrespective of the individual integration orders of those regressors. Furthermore, the spurious regression concern Granger and Newbold (1974) applies specifically to regressions among non-stationary I(1) series; it does not extend to I(0) regressors, which are stationary by definition and therefore cannot generate explosive dynamics. The only pairing in this system where spurious regression risk genuinely arises is the I(1), I(1) relationship between $CO_2$ and GDP, and this risk is directly addressed by the cointegration tests reported in Table 6. Accordingly, the empirical analysis is implemented through the following sequential procedure: (i) Testing for cross-sectional dependence. (ii) Testing for slope heterogeneity. (iii) Conducting panel unit root tests. (iv) Testing for long-run relationships among the variables. (v) Estimating the regression model using Driscoll-Kraay standard errors (Baltagi, 2009; Pesaran, 2006).

## 4. EMPIRICAL RESULTS AND DISCUSSIONS

### 4.1. Data Descriptions

Table 2 reports the descriptive statistics of the variables capturing environmental degradation, economic growth, foreign direct investment, renewable energy use, and industrialization. Environmental degradation, proxied by $CO_2$ emissions per capita, is measured in raw levels and ranges from 0.058 metric tons (minimum) to 23.626 metric tons (maximum), with a mean of 4.555 metric tons per capita. The variable is entered directly into the regression model without a logarithmic transformation. The positive skewness (1.643) and high kurtosis (4.700) confirm a right-skewed distribution driven by high-emission economies such as Brunei Darussalam and Singapore, reflecting substantial cross-country variation.

***Table 2: Data Description.***

| Variable | $CO_2$ | GDP | FDI | REU | IND |
|---|---|---|---|---|---|
| Mean | 4.555 | 10,278.880 | 5.269 | 36.185 | 35.913 |
| Std. dev. | 5.903 | 15,866.300 | 5.814 | 29.638 | 13.525 |
| Max | 23.626 | 68,218.810 | 31.621 | 91.100 | 76.432 |
| Min | 0.058 | 166.710 | - 2.757 | 0.000 | 9.692 |
| Skewness | 1.643 | 1.866 | 2.224 | 2.489 | 0.815 |
| Kurtosis | 4.700 | 5.418 | 8.252 | 1.766 | 4.185 |
| Jarque-Bera | 78.070 | 94.090 | 127.460 | 188.030 | 33.340 |

Economic growth, measured by GDP per capita in constant 2015 USD, ranges from USD 166.71 (minimum) to USD 68,218.81 (maximum), with a mean of USD 10,278.88, confirming extreme income heterogeneity across ASEAN economies. The pronounced range highlights strong developmental disparities among the sampled economies. Positive skewness and leptokurtic behavior further indicate that high-income economies such as Singapore exert disproportionate influence on the distribution.

Foreign direct investment (FDI) measured as net FDI inflows relative to GDP, averages 5.814 but exhibits high volatility, with values ranging from -2.757 to 31.621. The large skewness (2.224) and kurtosis (8.252) imply sporadic FDI surges. Renewable energy use (REU) shows a mean of 36.185, though with considerable dispersion, reflecting uneven renewable energy adoption. Finally, industrialization (IND), measured by industrial value added, displays relatively moderate variability and lower skewness, indicating a more balanced distribution. The Jarque–Bera statistics reject normality for all variables, justifying the use of robust econometric techniques.

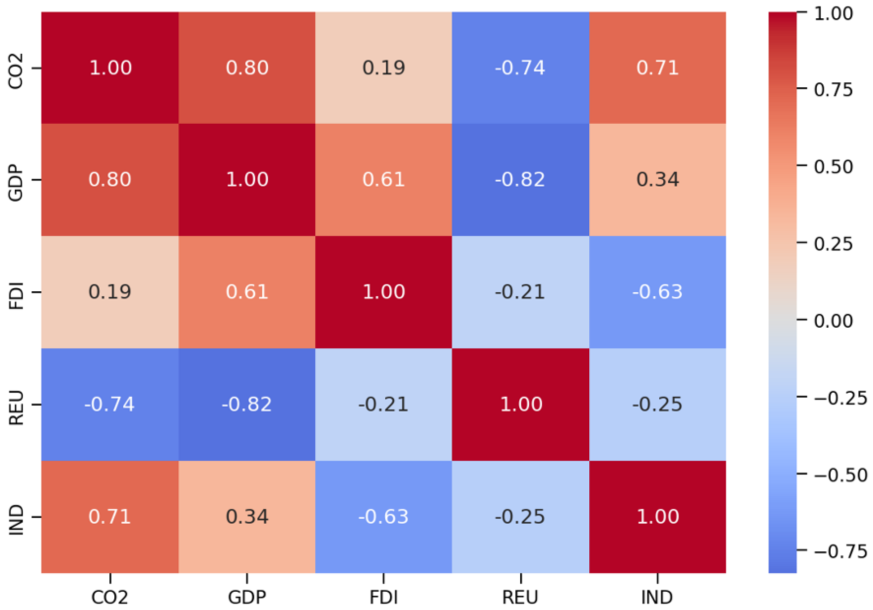


*Figure 1: Correlation Diagram.*

The correlation heatmap reveals pronounced relationships between economic activity and environmental indicators. $CO_2$ emissions are strongly and positively correlated with GDP (0.80) and industrialization (0.71), suggesting that economic growth and industrial expansion contribute significantly to higher emission levels. In contrast, renewable energy use exhibits a strong negative correlation with both $CO_2$ emissions (-0.74) and GDP (-0.82), highlighting its potential to mitigate environmental degradation amid economic growth. Foreign direct investment shows mixed correlations, being positively associated with GDP but negatively related to industrialization, indicating heterogeneous structural and environmental effects of capital inflows.

### *4.2. Regression Analysis*

Table 3 shows the results of the cross-sectional dependence tests, which indicate that most variables exhibit significant cross-sectional dependence. The Pesaran (2004) CD test shows that $CO_2$ emissions, GDP, renewable energy use, and industrialization are statistically significant at the 1% level, while foreign direct investment is significant at the 10% level. In addition, the Breusch and Pagan (1980) test provides highly consistent evidence, as all variables strongly reject the null hypothesis of cross-sectional independence at the 1% significance level. These findings suggest that cross-sectional units are mutually influenced by common shocks or economic linkages. Therefore, relying on traditional panel data models that ignore cross-sectional dependence may yield biased estimates, and estimation techniques accounting for such dependence are required.

*Tables 3: Cross-Sectional Dependence Test.*

| Variable | Pesaran (2004) | | Breusch & Pagan (1980) | |
|---|---|---|---|---|
| | CD test | P-value | Statistic | P-value |
| $CO_2$ | 18.093*** | 0.000 | 4,163.711*** | 0.0000 |
| GDP | 23.376*** | 0.000 | 4,953.690*** | 0.0000 |
| FDI | 1.855* | 0.064 | 2,642.692*** | 0.0000 |
| REU | -3.042*** | 0.003 | 5,041.311*** | 0.0000 |
| IND | 13.695*** | 0.000 | 4,683.342*** | 0.000 |

***** P<0.01, ** P<0.05, * P<0.1**

Table 4 illustrates the results of the slope heterogeneity test, which provides strong evidence in favor of heterogeneous slope coefficients across cross-sectional units. Both the Delta tilde and the adjusted Delta tilde statistics are highly significant at the 1% level, leading to a clear rejection of the null hypothesis of slope homogeneity. This implies that the impact of explanatory variables differs substantially across units, reflecting structural, institutional, or developmental disparities. These findings indicate that individual slope coefficients differ across ASEAN economies, a pattern consistent with the region's structural and developmental heterogeneity. However, as the study objective is to identify average panel-wide effects, and given the constraints of N = 10 with a quadratic EKC specification, the Driscoll-Kraay estimator is retained as the primary approach on the grounds established by Pesaran and Smith (1995), with its robust standard errors ensuring valid inference under the confirmed cross-sectional dependence.

***Table 4: Results Of the Slope Heterogeneity Test.***

| Variable | Test statistics | P-Value |
|---|---|---|
| **Delta tilde** | 15.187 *** | 0.000 |
| **Adjusted Delta tilde** | 16.979 *** | 0.000 |

***** P<0.01, ** P<0.05, * P<0.1**

The results of the CIPS and CADF unit root tests indicate a mixed order of integration among the study variables (Table 5). $CO_2$ emissions and GDP are non-stationary at levels but become stationary after first differencing, implying that they are integrated of order one, I(1). In contrast, FDI, renewable energy use, and industrialization are stationary at levels in at least one of the cross-sectionally augmented tests, suggesting they are I(0) variables. The consistency between CIPS and CADF results strengthens the robustness of these findings. Overall, the presence of both I(0) and I(1) variables justifies the use of econometric techniques that can accommodate mixed integration orders.

***Table 5: Stationarity Tests.***

| Variable | CIPS | | CADF | | Conclusion |
|---|---|---|---|---|---|
| | Level | First difference | Level | First difference | |
| $CO_2$ | -0.951 | -4.617 *** | -0.916 | -4.617*** | I(1) |
| GDP | -2.282 | -3.748 *** | -2.053 | -3.748 *** | I(1) |
| FDI | -2.934*** | -5.968 *** | -2.881*** | -5.968 *** | I(0) |
| REU | -2.390*** | -5.101 *** | -2.402** | -5.101 *** | I(0) |
| IND | -2.355** | -2.174** | -0.823 | -4.435*** | I(0) |

***** P<0.01, ** P<0.05, * P<0.1**

Table 6 reports the results of panel cointegration tests using the Westerlund and Pedroni approaches to examine long-run equilibrium relationships among the variables. The Westerlund variance ratio statistic is -1.329 with a p-value of 0.092, allowing rejection of the null hypothesis of no cointegration at the 10% significance level. This suggests the presence of a long-run relationship when cross-sectional dependence is taken into account. The Pedroni test further reinforces this evidence: the Modified Phillips-Perron t statistic is highly significant at the 1% level, while the Phillips-Perron t and ADF t statistics are significant at the 10% level. Taken together, these results provide suggestive evidence of long-run co-movement among the variables, with significance levels ranging from 1% to 10% across the test statistics. It should be acknowledged that the classical cointegration framework strictly requires all variables to be I(1); however, following Pesaran, Shin and Smith (2001), long-run relationships can still be meaningfully examined in mixed I(0)/I(1) systems when the dependent variable here $CO_2$ emissions, is integrated of order one. Under this interpretation, the cointegration results are treated as indicative of a stable long-run relationship rather than as formal proof of cointegration in the Engle-Granger sense, and subsequent estimation proceeds accordingly.

***Table 6: Results Of Cointegration Test.***

| Test | T- statistics | P-Value |
|---|---|---|
| **Westerlund** | | |
| Variance ratio | -1.329 | 0.092 |
| **Pedroni** | | |
| Modified Phillips-Perron | 2.372* * * | 0.009 |
| Phillips-Perron | 1.366* | 0.086 |
| Augmented Dickey-Fuller | 1.291* | 0.098 |

***** P<0.01, ** P<0.05, * P<0.1**

*Note: The Westerlund variance ratio and Pedroni tests were originally derived under the assumption that all variables are I(1); the presence of I(0) regressors (FDI, REU, IND) therefore requires that results be interpreted with caution. However, three considerations support their continued use as complementary diagnostics. First, Pesaran, Shin and Smith (2001, p. 290) establish that long-run relationships can be validly examined in mixed I(0)/I(1) systems when the dependent variable is I(1) a condition satisfied here by $CO_2$ emissions. Second, spurious regression risk pertains solely to non-stationary series: I(0) regressors are stationary and cannot produce spurious dynamics, so the only pairing requiring cointegration evidence is $CO_2$ (I(1)) and GDP (I(1)),* *which the tests directly address. Third, the Westerlund (2005) variance ratio statistic, unlike the Westerlund (2007) error-correction test, is based on the ratio of long-run to short-run panel residual variance and is less sensitive to the integration order of individual regressors. Accordingly, the cointegration results are interpreted as indicative evidence of long-run co-movement among the variables in the spirit of Pesaran, Shin and Smith (2001), rather than as formal cointegration in the Engle-Granger sense.*

Based on Table 7, the estimation results using Driscoll-Kraay standard errors suggest evidence of long-run co-movement determinants of $CO_2$ emissions in ASEAN countries, accounting for cross-sectional dependence, heteroskedasticity, and serial correlation. GDP exhibits a positive and highly significant coefficient at the 1% level, indicating that increases in per capita income are associated with higher $CO_2$ emissions. This finding reflects the fact that economic expansion intensifies energy demand through higher consumption of electricity, transportation services, housing, and other energy-intensive goods. Moreover, rising income levels are typically accompanied by accelerated industrialization and urbanization, which expand production scale and fossil-fuel use, thereby increasing emissions. This result is consistent with prior evidence reported by Fodha and Zaghdoud (2010), Chang (2010), and Mikayilov, Galeotti and Hasanov (2018).

Importantly, the coefficient of $GDP^2$ is negative and statistically significant at the 1% level. Together with the positive GDP coefficient, this provides empirical support for the EKC mechanism in the ASEAN context. The negative quadratic term implies that the income elasticity of $CO_2$ emissions turns negative beyond a critical threshold estimated here at approximately USD 42,932 per capita driven by the structural shift of maturing economies toward less carbon-intensive service sectors, the greater fiscal capacity to invest in abatement technology, and the strengthening of environmental regulatory frameworks that typically accompany rising income levels. This finding aligns well with the seminal works and subsequent studies of (Dietz & Rosa, 1994; Espoir, Sunge, & Bannor, 2023; Grossman & Krueger, 1995; Özokcu & Özdemir, 2017; Salari, Javid, & Noghanibehambari, 2021).

***Table 7: Results Of Estimation Model Using Driscoll-Kraay Standard Errors.***

| Variable | Coefficient | Driscoll-Kraay Std. errors | T-statistics | p-value |
|---|---|---|---|---|
| GDP | 5.86e-05*** | 9.17e-06 | 6.391 | 0.000 |
| $GDP^2$ | -6.82e-10*** | 1.29e-10 | -5.312 | 0.000 |
| FDI | 0.013* | 0.008 | 1.881 | 0.068 |
| REU | -0.046*** | 0.002 | -18.692 | 0.000 |
| IND | 0.019*** | 0.004 | 4.771 | 0.000 |
| Const | 1.090*** | 0.264 | 4.131 | 0.000 |

***** P<0.01, ** P<0.05, * P<0.1**

*Note: Although the slope heterogeneity test rejects coefficient homogeneity (Table 4), the Driscoll-Kraay estimator is retained as the primary specification because (i) the study targets average ASEAN-wide effects rather than country-specific parameters, (ii) Pesaran and Smith (1995) establish consistency of pooled estimators for mean group effects under slope heterogeneity as $T \to \infty$, and (iii) N = 10 renders Mean Group estimation subject to substantial finite-sample imprecision given the quadratic EKC specification.*

Regarding economic growth and the EKC hypothesis, the confirmation of an inverted U-shaped relationship between GDP per capita and $CO_2$ emissions is consistent with the foundational predictions of Grossman and Krueger (1995) and subsequent studies by Özokcu and Özdemir (2017), Salari, Javid and Noghanibehambari (2021), and Espoir, Sunge and Bannor (2023). The positive linear coefficient on GDP reflects the scale effect: as income rises, households and firms consume more energy-intensive goods and services, expanding the carbon footprint of production. However, the negative and significant coefficient on $GDP^2$ confirms that this relationship is not monotonic. Beyond a certain income threshold, implied by the turning point of the estimated quadratic function, environmental quality begins to improve. Based on the estimated coefficients of GDP and its squared term, the turning point of the Environmental Kuznets Curve (EKC) is identified using the formula $GDP^* = -\frac{\alpha_1}{2\alpha_2}$, yielding an estimated income threshold of approximately USD 42,932 per capita (constant 2015 prices). Although a formal Fieller (1954) confidence interval requires the full variance-covariance matrix of the estimated coefficients, the statistical validity of the turning point as an interior maximum can be assessed from the regression output in Table 7. Specifically, the Lind and Mehlum (2010) conditions for a genuine inverted-U relationship require: (i) the linear income coefficient is positive and statistically significant satisfied here ($\alpha_1$ = 5.86e-05, $p < 0.01$); (ii) the quadratic coefficient is negative and statistically significant satisfied here ($\alpha_2$ = - 6.82e-10, $p < 0.01$); and (iii) the implied turning point falls strictly within the observed income range of the sample. The estimated threshold of USD 42,932 lies within the sample range of USD 166.71 to USD 68,218.81, confirming that the inverted-U pattern represents a genuine interior maximum rather than a monotone or boundary relationship. Taken together, these three conditions confirm that the EKC turning point is statistically meaningful, consistent with the inferential logic underlying the Lind-Mehlum test. This turning point reflects the income level at which the marginal effect of economic growth on $CO_2$ emissions shifts from positive to negative. A comparison between this threshold and country-specific income levels across ASEAN indicates that only Singapore has exceeded the identified turning point, while the remaining nine countries remain on the upward-sloping segment of the EKC. This finding implies that, for most ASEAN economies, current income growth continues to be associated with increasing $CO_2$ emissions rather than automatic environmental improvements. Accordingly, the proposition that rising income levels eventually lead to better environmental outcomes should be interpreted with caution in the ASEAN context, as such effects appear to materialize only beyond a relatively high-income threshold. This improvement is typically attributed to the income effect on environmental preferences, the structural shift toward less carbon-intensive service sectors, and the greater capacity of higher-income economies to invest in cleaner technologies and enforce environmental regulation. Importantly, not all ASEAN economies have yet reached this turning point, implying that the near-term trajectory of $CO_2$ emissions in lower-income members such as Cambodia, Lao PDR, and Myanmar is likely to remain upward as their economies continue to expand. This heterogeneity within the region underscores the importance of differentiated, country-specific policy responses rather than uniform regional mandates.

Regarding foreign direct investment, FDI inflows exhibit a positive and marginally significant association with $CO_2$ emissions ($p = 0.068$), weakly consistent with the pollution haven hypothesis and aligned with results reported by Pata, Dam and Kaya (2023) for ASEAN countries and Pao and Tsai (2011) for a broader cross-country sample. In the ASEAN context, several structural factors help explain this outcome. First, a substantial share of FDI in the region has historically been directed toward manufacturing, resource extraction, and export-processing zones sectors characterized by high energy intensity and carbon output. Second, competitive pressure among ASEAN member states to attract foreign capital may have led to regulatory leniency or the implicit tolerance of pollution-intensive investment projects. Third, the technology spillover effects associated with FDI are central to the pollution halo hypothesis and appear insufficient to offset the scale expansion of emissions, at least within the current study period. This result contrasts with evidence from EU transition economies (Hu et al., 2021) and the BRICS countries (Wang et al., 2023), where green FDI and long-run efficiency gains have been found to reduce environmental pressure. The divergence likely reflects differences in institutional quality, regulatory capacity, and the sectoral composition of investment flows. As emphasized by Tripathy et al. (2025), strong governance is a prerequisite for FDI to generate positive environmental outcomes, a condition that remains unevenly met across ASEAN.

Regarding renewable energy, the strong negative and statistically significant effect of renewable energy consumption on $CO_2$ emissions is one of the most robust findings of the study, and is broadly consistent with Zoundi (2017), and Szetela et al. (2022). The result confirms that transitioning from fossil fuels toward renewable sources, including hydropower, solar, wind, and geothermal energy, constitutes an effective decarbonization channel in the ASEAN context. Mechanically, renewable energy substitutes for combustion-based electricity generation and reduces the carbon intensity of the energy mix, thereby lowering emissions per unit of output. Beyond the substitution effect, renewable energy deployment can also stimulate technological learning and innovation in the clean energy sector, generating dynamic efficiency gains over time. The magnitude of this effect is noteworthy: the coefficient is among the largest in absolute terms in the regression, suggesting that renewable energy policy is potentially the most powerful lever available to ASEAN policymakers seeking to mitigate emissions in the short to medium run. This finding aligns with the broader argument by Chen, Pinar and Stengos (2022) that the effectiveness of renewable energy is amplified by institutional strength, pointing to the co-importance of regulatory capacity and energy investment in shaping environmental outcomes.

Regarding industrialization, the positive and significant effect on $CO_2$ emissions confirms that industrial expansion remains a primary driver of carbon pollution in ASEAN, consistent with Liu and Bae (2018) and Dogan and Seker (2016). In most

ASEAN economies, industrial growth is still largely powered by fossil fuels, and the adoption of energy-efficient production technologies has lagged behind the pace of structural transformation. The result also aligns with (Mentel et al., 2022), who document a similar positive industrialization emissions relationship in European and Central Asian countries but note that renewable energy can partially offset this effect. Taken together, the findings suggest that industrial policy in ASEAN must be deliberately redesigned to incorporate green transition objectives through technology upgrading, energy efficiency standards, and incentives for cleaner production processes if the region is to decouple industrial growth from environmental degradation.

Collectively, these findings reveal a nuanced picture of the growth environment nexus in ASEAN. Economic growth and industrialization generate environmental pressure through scale and composition effects, while renewable energy provides a meaningful counterforce. FDI, in its current form, tends to amplify rather than mitigate emissions, underscoring the need for qualitative improvements in investment governance. The coexistence of these dynamics within a single integrated framework and across a region as diverse as ASEAN highlights the complexity of designing effective environmental policy and the inadequacy of one-dimensional approaches.

## 5. CONCLUSION AND POLICY IMPLICATIONS

### *5.1. Conclusion*

This study investigates the long-run relationship between environmental degradation, economic growth, foreign direct investment, renewable energy consumption, and industrialization in ASEAN countries over the period 1990-2024. Using a balanced panel framework and Driscoll-Kraay standard errors to address cross-sectional dependence and slope heterogeneity, the empirical results offer several important insights. Economic growth exerts a positive and statistically significant effect on $CO_2$ emissions, indicating that income expansion in ASEAN countries has historically been associated with increased environmental pressure. However, the negative and significant coefficient of the squared income term confirms the existence of an inverted U-shaped Environmental Kuznets Curve (EKC). The results further reveal that the growth emissions relationship is not monotonic: the EKC turning point identified at approximately USD 42,932 per capita implies that income growth currently intensifies environmental pressure across the nine ASEAN economies yet to cross this threshold, while only Singapore has entered the downward segment of the curve. Foreign direct investment exhibits a positive and marginally significant association with $CO_2$ emissions, providing weak evidence consistent with the pollution haven hypothesis; this result should be interpreted cautiously given its marginal statistical significance and the heterogeneous institutional environments across member states. Renewable energy consumption exerts the strongest mitigating effect in the model, confirming its role as the most effective near-term decarbonisation lever available to ASEAN policymakers. Finally, industrialisation is associated with higher emissions, reflecting the continued dependence of regional production structures on fossil fuels. Collectively, these findings underscore that economic growth alone cannot guarantee environmental improvement; targeted policy interventions in energy transition, investment screening, and industrial upgrading are essential complements to income-led development across the ASEAN region.

### *5.2. Policy Implications*

The empirical findings of this study carry several policy implications for ASEAN countries, particularly in the context of balancing economic development with environmental sustainability. First, given that economic growth initially raises $CO_2$ emissions before reaching a turning point, ASEAN policymakers should actively guide the growth process toward a green development pathway. This entails integrating environmental objectives into national development strategies rather than treating environmental protection as a secondary concern. Policies that promote energy efficiency, low-carbon technologies, and sustainable urban planning can help reduce the environmental costs of growth before income levels naturally reach the EKC turning point.

Second, the positive relationship between foreign direct investment and emissions highlights the importance of improving the environmental quality of FDI rather than simply increasing its volume. ASEAN governments may consider strengthening environmental screening mechanisms for incoming investment projects, prioritizing those that employ cleaner technologies and sustainable production methods. Enhancing regulatory enforcement and harmonizing environmental standards across the region could also help mitigate the risk of regulatory competition that attracts pollution-intensive activities.

Third, the strong mitigating effect of renewable energy consumption suggests that expanding renewable energy deployment should remain a central policy priority. Governments can support this transition by increasing public investment in renewable infrastructure, providing stable regulatory frameworks, and encouraging private sector participation through targeted incentives such as feed-in tariffs, tax credits, or concessional financing. Such measures can accelerate the substitution of fossil fuels while supporting long-term energy security.

The extreme income heterogeneity within ASEAN, from approximately USD 1,300 per capita in Cambodia to USD 65,000 in Singapore, calls for differentiated policy responses rather than a uniform regional mandate.

For lower-income ASEAN members (Cambodia, Lao PDR, Myanmar), which remain on the upward-sloping segment of the EKC, three priority actions are recommended: (i) carbon-conditional development assistance that couples growth investment with binding emission intensity standards; (ii) leapfrogging strategies that direct industrial investment into less carbon-intensive sectors from the outset, avoiding replication of the fossil-fuel-dependent industrialisation path of earlier developers; and (iii) capacity building for environmental regulatory agencies to ensure that incoming FDI meets minimum environmental performance benchmarks.

For middle-income ASEAN members (Indonesia, Philippines, Vietnam, Thailand, Malaysia), which are in active industrial transformation and are the primary drivers of regional emission growth, recommended actions include: (i) mandatory energy intensity targets for the manufacturing sector; (ii) green industrial parks that require clean energy certification as a condition for preferential investment incentives; and (iii) integration of carbon pricing instruments, whether emissions trading schemes or carbon taxes — to internalise the social cost of industrial emissions.

For the high-income ASEAN member (Singapore, and to a lesser extent Brunei Darussalam), which has already crossed the identified EKC turning point, policy should focus on: (i) financing and technology transfer to lower-income ASEAN partners as a regional public good; (ii) strengthening environmental conditionality attached to Singapore-based FDI flows directed into the rest of ASEAN; and (iii) harmonising environmental reporting standards across the bloc to improve data comparability and regional policy learning.

Fourth, the positive impact of industrialization on emissions indicates a need to promote cleaner industrial transformation. Policies that encourage technological upgrading, energy-efficient manufacturing processes, and circular economy practices can help decouple industrial growth from environmental degradation. Support for research and development, as well as capacity-building for firms to adopt cleaner production technologies, can be effective in this regard.

While the empirical results confirm that renewable energy consumption significantly reduces $CO_2$ emissions in ASEAN, translating this finding into actionable policy requires acknowledgement of the structural and institutional barriers constraining the renewable energy transition in the region.

First, grid infrastructure and intermittency: most ASEAN member states lack the transmission grid capacity and cross-border interconnection to integrate variable renewable generation (solar and wind) at scale. The ASEAN Power Grid initiative remains incomplete, and several economies depend on isolated mini-grids. Without investment in smart grid infrastructure, energy storage, and regional interconnection, large-scale renewable deployment faces significant technical constraints regardless of installed capacity.

Second, financing and investment gaps: the International Energy Agency estimates that Southeast Asia requires approximately USD 190 billion per year in clean energy investment to achieve net-zero pathways, roughly four times current clean energy capital flows. Access to concessional climate finance through Just Energy Transition Partnerships (JETPs), which Vietnam and Indonesia have already entered, remains uneven across the bloc. Smaller economies such as Cambodia and Lao PDR face higher capital costs and more limited domestic financing capacity.

Third, policy and regulatory consistency: feed-in tariff schemes, renewable energy certificates, and net-metering regulations differ markedly across ASEAN member states, creating investor uncertainty and impeding cross-border clean energy investment. The finding in this study that FDI's environmental effect is positive but only weakly significant is consistent with the interpretation that the current regulatory environment does not yet channel foreign capital systematically into clean sectors.

Fourth, socioeconomic and distributional concerns: rapid decarbonisation of the energy sector can impose transition costs on communities dependent on coal mining, fossil fuel processing, and related industries — a consideration particularly salient in Indonesia and Vietnam, where coal remains a major employer. Policies that address just transition objectives, including retraining programmes and social protection floors, are therefore necessary complements to renewable energy mandates.

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