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Impact of industrialization and renewable energy on carbon dioxide emission in 9 ASEAN countries

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Abstract

Purpose — This research investigates the relationship between ASEAN's industrialization, renewable energy, and CO2 emissions. The primary objectives are to assess the existence of the Environmental Kuznets Curve (EKC) in ASEAN and to explore the potential mediating effect of renewable energy in the relationship between industrialization and CO2 emissions.

Methods — The study utilizes the PMG-ARDL estimation method in nine ASEAN countries from 1990 to 2019, providing short- and long-term analyses of the variables involved.

Findings — The finding reveals the presence of the EKC in ASEAN in the short term for most member states. It also finds that renewable energy mediates the relationship between industrial value-added and CO2 emissions, with renewable energy adoption altering the turning point of per capita CO2 emissions during industrialization in several ASEAN nations.

Implication — The findings suggest that transitioning to renewable energy can help mitigate the environmental impact of ASEAN's industrial development. Thus, member states committed to energy targets should prioritize deploying renewable energy in their industrial sectors to achieve environmental benefits.

Originality — This research contributes to the existing literature by specifically examining the interplay between industrialization, renewable energy, and CO2 emissions in ASEAN. The use of the PMG-ARDL estimation method and the focus on the mediating role of renewable energy add originality to the study.

Keywords — Industrialization, renewable energy, carbon emissions, Environmental Kuznets Curve (EKC), ASEAN

Introduction

Over the past few years, addressing climate change and reducing greenhouse gas (GHG) emissions has been a critical action that should be taken. In 2018, the Intergovernmental Panel on Climate Change (IPCC) put forth a crucial proposal, advocating for achieving net-zero emissions by 2050 as a key strategy to restrict global warming to 1.5° Celsius. This recommendation underscores the pressing need for decisive action in addressing the climate crisis. However, the current trajectory suggests that GHG emissions will continue to rise until 2030, leading to a global temperature increase of 2.1° to 3.9° Celsius (UNEP, 2020). The ASEAN Centre for Energy (ACE, 2020) predicts a significant increase of 34% to 147% in energy-related GHG emissions by 2040. The

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ASEAN region must lead a decarbonizing revolution (Lewis & Maslin, 2015) to achieve the net-zero emissions target by the end of the century.

ASEAN has taken some action to mitigate GHG emissions and proactively address climate change risks by implementing the ASEAN Plan of Action for Energy Cooperation (APAEC) 2016-2025. The primary objective of APAEC is to bolster energy connectivity and market integration within ASEAN, aiming to achieve comprehensive energy security, accessibility, affordability, and sustainability for all member nations. Some of the key APAEC set an ambitious target of incorporating 23% renewable energy in the ASEAN energy mix and achieving 35% installed power capacity from renewable sources by 2025.

Over recent years, the ASEAN region has experienced rapid economic growth, which is expected to continue in the long term (Lu, 2017). While the industrial sector drives economic development in many ASEAN countries, it also contributes to environmental issues such as deforestation and reliance on non-renewable energy sources (Hoad, 2015). Forecasts indicate that long-term carbon and GHG emissions from fossil fuel combustion will significantly impact climate change trends (Ahmed et al., 2021). Consequently, ASEAN faces the unique challenge of achieving a balance between economic growth and environmental preservation, necessitating a comprehensive study of the role of renewable energy within the framework of the Environmental Kuznets Curve (EKC) hypothesis for CO2 emissions.

This research makes several notable contributions by studying industrialization's environmental impact. Firstly, the study explores the impact of industrialization on emissions in the EKC hypothesis, considering the influence of renewable energy utilization. While most EKC hypotheses traditionally use GDP or income to measure a country's development, we recognize the significant role of industrialization in driving ASEAN's GDP growth. Therefore, industrialization is a better proxy for economic progress (Rahman & Alam, 2022). Secondly, this study employs the PMG-ARDL estimator, which imposes homogeneity in the long-run coefficient while incorporating country-specific effects. This approach enables a more precise analysis of the linkage between renewable energy, industrialization, and CO2 emissions.

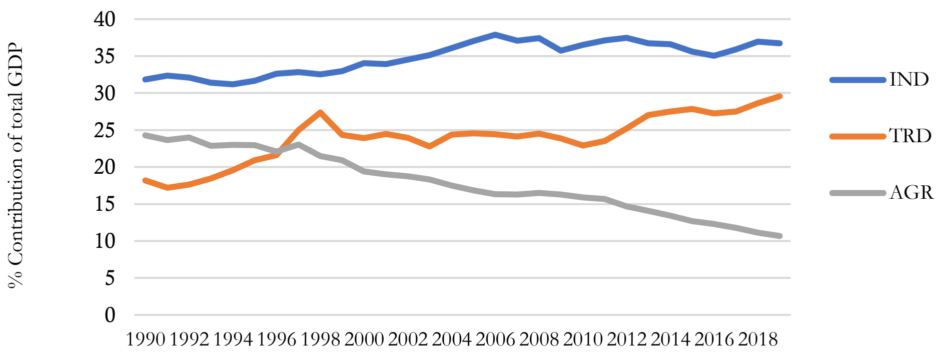


Figure 1. Change in ASEAN's Share of GDP from Agriculture, Industry, and Trade

The EKC hypothesis offers a structured framework for examining the dynamic correlation between environmental impacts and economic growth across temporal dimensions. Early economic growth, dominated by agricultural production and heavy industry, often increases environmental pollution (Dasgupta et al., 2002). However, pollution levels decrease as the service and industrial sectors expand (Figure 1). The EKC hypothesis typically measures environmental proxies, such as carbon dioxide emissions, with economic development indicators, such as GDP or income. In the case of ASEAN, industrialization has been used to examine the EKC theory (Apergis & Ozturk, 2015; Aquilas et al., 2022; Bulut, 2019; Rahman & Alam, 2022). According to Rahman and Alam (2022), industrialization, which increases CO2 emissions, is a more suitable proxy for economic progress. Moreover, the transformation driven by industrialization contributes significantly to ASEAN's GDP.

Figure 2 shows the dynamic shifts of the EKC under varying conditions. As more countries embrace renewable energy to mitigate carbon emissions, the curve's turning point moves from point

A to point B, leading to an accelerated process (from EKC1 to EKC0). Conversely, neglecting renewable energy adoption can hold the turning point, resulting in a shift from EKC0 to EKC2, with the turning point shift from point A to point C. A slower progression towards the inflection point implies that during the early stages of economic expansion, the costs of environmental degradation and trade-offs between economic growth and environmental sustainability are higher.

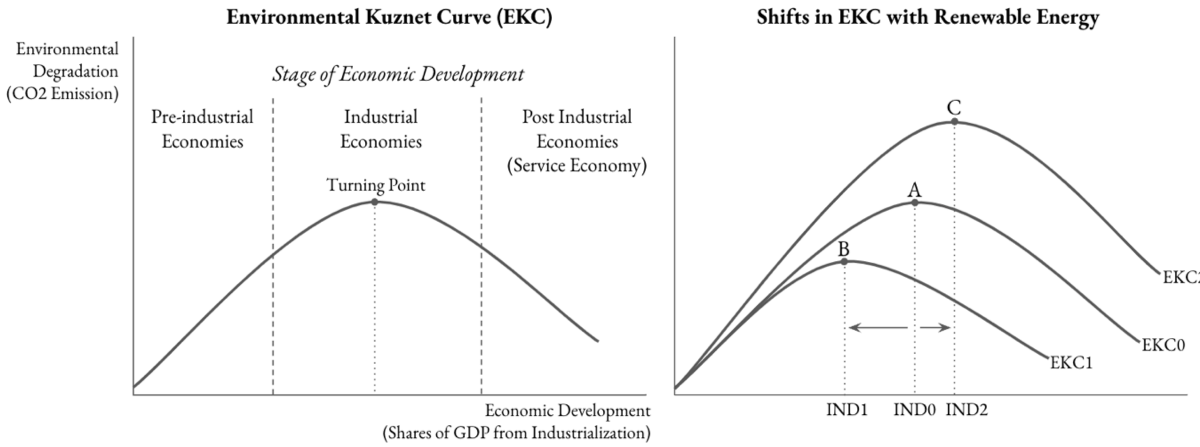


Figure 2. Shifts in Environmental Kuznets Curve

Despite extensive research on the relationship between economic development and the environment using the EKC theory, limited attention has been devoted to studying this phenomenon within the context of ASEAN, mainly focusing on industrialization and renewable energy as primary factors. Furthermore, prior studies have yet to validate the presence of the EKC hypothesis in ASEAN. Chandran and Tang (2013) studied the EKC in five ASEAN countries. Liu et al. (2017) examined Indonesia, Malaysia, the Philippines, and Thailand from 1970 to 2013 and found no evidence of a long-term inverted U-shaped EKC. However, Gillani and Sultana (2020) investigated the EKC framework for selected ASEAN states from 1970 to 2019 and strengthened the the result through increased energy efficiency and the greater adoption of renewable energy sources.

The results of ASEAN-specific research on the EKC varied among researchers. Saboori and Sulaiman (2013) found a U-shaped curve in Singapore and Thailand, but the relationship was statistically insignificant in Malaysia. Indonesia and the Philippines exhibited a U-shaped curve at a 10% significance level, indicating that they are still in the growth phase of the curve. These varied outcomes can be related to the five ASEAN states' different economic development stages.

The correlation between industrialization and CO2 emissions has been a growing scholarly study. China has witnessed notable environmental degradation despite the economic advantages of rapid industrialization. Empirical investigations have demonstrated that a 1% increase in industrialization in China results in a 0.3% rise in CO2 emissions (Liu & Bae, 2018). Similarly, Li and Lin (2015), utilizing the STIRPAT model, found a positive association between industrialization and CO2 emissions in low- and middle-income countries but no significant impact in high-income countries. These findings indicate that industrialization plays a role in CO2 emissions, particularly during the early stages of economic development, when it influences energy demand and consumption patterns. However, industrialization can also facilitate climate change adaptation and mitigation by improving energy efficiency and utilizing infrastructure and agglomeration (Zhou et al., 2013).

Within ASEAN countries, industrialization has been pinpointed as a primary driver of environmental sustainability challenges, evident in the substantial levels of CO2 emissions stemming from the transportation sector across nations like Malaysia, Indonesia, Thailand, the Philippines, Singapore, and Laos during the period from 1995 to 2015 (Jermsittiparsert, 2021). Tarasawatpipat and Mekhum (2020) also found a valid link between industrialization and greenhouse gas emissions in ASEAN countries, with varying degrees of significance in different nations.

The importance of environmentally friendly energy, particularly renewable energy, in reducing CO2 emissions cannot be overstated (Bölük & Mert, 2014; Shafiei & Salim, 2014). Replacing fossil fuels with renewable energy sources has the potential to reduce CO2 emissions significantly. Multiple studies have investigated the impact of renewable energy on CO2 emissions in ASEAN countries. For instance, Abbasi et al. (2020) examined the association between renewable energy and carbon dioxide emissions in Thailand from 1980 to 2018, utilizing the ARDL regression approach to assess both short- and long-term effects. Their findings supported the notion that transitioning to renewable energy consumption can assist Thailand in achieving its long-term CO2 emission reduction objectives. Similarly, Vo et al. (2019) studied Malaysia, the Philippines, and Thailand and identified a one-way causal relationship between economic growth, renewable energy usage, and CO2 emissions. However, they observed that the current level of renewable energy adoption is insufficient to mitigate CO2 emissions effectively.

While there is a consensus that renewable energy can help mitigate emissions, the indirect impact of renewable energy on pollution has yet to be extensively explored. Some studies have employed interaction models to investigate how energy usage influences the relationship between carbon emissions and variables related to economic growth. For example, Shah et al. (2022) argued that adopting renewable energy can reduce the positive contribution of agriculture to CO2 emissions, thereby offsetting agricultural contributions to climate change. Tang et al. (2020) evaluated the role of renewable energy in the industrial sector of OECD nations, while Dargahi and Khameneh (2019)observed the effects of renewable energy on structural shifts in OECD countries. However, the effects of renewable energy on carbon dioxide emissions can vary depending on the specific economic factors characterizing each country (Jimenez & Mercado, 2014).

Although the amount of renewable energy required to address environmental degradation remains inconclusive, it is widely acknowledged that increasing renewable energy usage in ASEAN countries will lead to lower CO2 emissions (Shafiq et al., 2020). Adopting renewable energy can contribute to reducing environmental damage. Liu et al. (2017), Nathaniel and Khan (2020), Zeraibi et al. (2021) have all demonstrated that renewable energy can effectively reduce CO2 emissions in ASEAN countries. Expanding renewable energy use fosters technological innovation and helps decrease ecological footprints. However, it is important to recognize that the extent of this impact may vary.

This current study aims to shed light on the moderating effect of renewable energy on the relationship between industrialization and CO2 emissions in ASEAN countries. By exploring this relationship within the framework of the EKC hypothesis, the research seeks to contribute to a deeper understanding of the dynamic relation between economic development, renewable energy adoption, and environmental sustainability. The findings of this study can offer valuable insights for policymakers and stakeholders in the ASEAN region as they strive to achieve their climate goals and promote sustainable economic growth.

Methods

This research uses data from the World Bank Development Indicator. ASEAN member states included in this study are Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, and Thailand from 1990 to 2019, using the Pooled Mean Group-Autoregressive Distributed Lag (PMG-ARDL) estimator. Table 1 shows all variables and their descriptive statistics.

Table 1. Variable description and descriptive statistics

Variable	Description	Unit	Mean	Standard Deviation	Min	Max
CO	Carbon dioxide emission per capita	metric tons per capita	4.20	5.19	0.09	20.84
IND	Value added of Industry sectors to GDP	current USD	34.83	13.95	10.20	74.11
REN	Share of renewable energy consumption.	%	36.75	31.49	0.010	91.11
GDP	Gross domestic product per capita	current USD	8625.78	14008.19	49.26	66859.34
OPN	Share of value added of trade sectors to GDP.	% Ratio	117.63	94.87	11.85	437.32
AGR	Share of value added of agriculture sectors to GDP.	% Ratio	17.85	15.92	0.03	57.14

We expand the EKC framework by integrating the industrialization and renewable energy sectors and a set of empirically suggested controls. The comprehensive empirical model can be represented as follows:

$$CO_{it} = f(IND, RE, GDP, OPN, AGR)_{it} \quad (1)$$

The formulated econometric model is presented in equation (2):

$$lnCO_{it} = \beta_0 + \beta_1 lnIND_{it} + \beta_2 lnIND^2{}_{it} + \beta_3 RE_{it} + \beta_4 lnIND \cdot RE_{it} + \beta_5 lnGDP_{it} + \beta_6 OPN_{it} + \beta_7 AGR_{it} + \varepsilon_{it} \quad (2)$$

Where $\ln CO$ is the log natural of emissions per capita, $\ln IND$ is the value added of industry, $\ln IND^2$ is log natural square of value added of the industry. RE denotes renewable energy consumption as % total energy use; $\ln IND \cdot RE$ is the interaction terms of renewable energy and industrialization; i represents country, t represents time, and ε is the regression error term. For variable control, $\ln GDP$ denotes a natural logarithm of GDP per capita that represents the welfare of a country; OPN is trade openness calculated from the share of value added of trade (%); AGR is the share of value added of agriculture (%).

The EKC framework is a commonly used theoretical model for evaluating the relationship between development and CO2 emissions. The model initially proposes a quadratic relationship between GDP and environmental degradation. We augmented the EKC hypothesis by using IND and IND^2, which are also used as a proxy for economic development. Using the value of industrialization of each ASEAN country helps to explore the moderating impact of how renewable energy use mediates the relationship between industry value adds and CO2 emissions. The study also uses the moderating effect by multiplying industrialization and renewable energy $(IND \cdot RE)$ into the equation.

Based on *a priori* theory, the coefficient of $\ln IND$ should be positive ($\beta_1 > 0$) while the coeffithe cient of $\ln IND^2$ should be negative ($\beta_2 < 0$) to support the EKC hypothesis. The hypothesis expects that industrialization has an inverted U-shaped non-linear impact on emissions. Otherwise, the EKC theory is not supported. A positive interaction is expected between RE and CO ($\beta_3 > 0$). Likewise, for interaction variables of $\ln IND \cdot RE$ and CO, both positive and negative can be obtained according to the magnitude of industrialization in the coefficient ($\beta_4 > 0$). A positive connection is expected between $\ln GDP$ and CO ($\beta_5 > 0$). A positive interaction is anticipated between OPN and CO ($\beta_6 > 0$). A positive association is also expected between AGR and CO ($\beta_7 > 0$).

Moreover, calculating the elasticity will tell us how carbon dioxide emission changes when industrialization changes, when other covariates are assumed to be held constant:

$$e_{CO,IND} = \frac{d(\ln CO)}{d(\ln IND)} = \frac{dCO}{dIND} \cdot \frac{IND}{CO} = (\beta_1 + 2\beta_2 \ln IND + \beta_4 RE) \quad (3)$$

Equation (3) illustrates the elasticity effect of industrialization on carbon dioxide emissions, considering the integration of renewable energy in industrial activities. Industrialization is expected to impact the change in the carbon dioxide emissions rate. Consequently, the impact of renewable energy on mitigating the adverse effects of industrialization depends on the signs of the coefficients; if the coefficient of the industrial sector is positive ($\beta 1 > 0$) and the coefficient of the interaction term is negative ($\beta 4 < 0$), renewable energy will have a favorable influence in reducing the adverse impact of industrialization on emissions. Conversely, if $\beta 1 < 0$ and $\beta 4 > 0$, industrialization will hinder the positive effects of renewable energy on emissions. The statistical significance of the interaction term in these models will confirm the existence of moderating roles. Thus, this study postulates that the share of renewable energy may mitigate the effect of industrialization on carbon dioxide emissions. The turning point or maximum point slope is reached when the value equals 0, allowing us to calculate the turning point of the EKC when renewable energy scores are at zero, as follows:

$$\widehat{IND} = e^{-\frac{\beta_1}{2\beta_2}} \tag{4}$$

Moreover, to assess the influence of renewable energy, the turning point of the EKC is computed by incorporating the supplementary interaction variable, as demonstrated in the following equation:

$$\widehat{IND} = e^{-\frac{\beta_1+\beta_4 RE}{2\beta_2}} \tag{5}$$

We use several approaches to assess the impact of renewable energy on the relationship between industrialization and emissions. Initially, we conducted a cross-sectional dependence (CSD) test to identify any potential issues of cross-sectional dependency in the panel data series. Specifically, the Breusch and Pagan Lagrange Multiplier (LM) test is utilized as the primary method to detect such dependencies within the dataset. The Pesaran (2004) cross-sectional dependency test is also employed, particularly suitable for handling datasets with limited cross-sectional observations and short-time dimensions. The Pesaran CSD statistic tests the null hypothesis of no cross-sectional dependence. This test statistic is distributed as a two-tailed standard normal distribution, $N(0,1)$, when N tends to infinity (∞) and T is sufficiently large.

Mandala and Wu's estimation method involved using four-panel unit root tests to assess variable stationarity. Stationary tests used are Levin-Lin-Chao, Im, Pesaran, and Shin, Augmented Dickey-Fuller (ADF), and Phillips–Perron tests. These tests are used to determine the integration orders of the variables. A cointegration test investigates potential long-term relationships between two or more non-stationary time series variables. This technique is utilized to ascertain whether the non-stationary time series variables are in long-term equilibrium. The panel cointegration test proposed by Kao (1999) is utilized to determine the long-term integration of the panel series.

After conducting a cointegration test, we employ the PMG-ARDL estimator to strengthen the analysis of short-term cross-sectional units in the sample panel, which is better than other estimators. It estimates homogenous long-run effects while allowing for heterogeneous short-run impacts. Our analysis focuses on the seven largest emerging economies with identical long-term dynamics. However, due to country-specific macroeconomic factors, short-term dynamics may vary. Therefore, equation (6) provides a re-parametrization of equation (2) that characterizes the long-run and short-run cointegration equation of a dynamic panel.

$$\Delta \ln CO_{it} = \phi_i EC_{it} + \sum_{j=1}^{p-1} \lambda_{1j} \Delta \ln CO_{t-j} + \sum_{j=1}^{q-1} \theta \Delta X'_{i,t-j} + \varepsilon_{it} \Delta X = \begin{bmatrix} \Delta \ln IND \\ \Delta \ln IND^2 \\ \Delta RE \\ \Delta \ln IND \cdot RE \\ \Delta \ln GDP \\ \Delta OPN \\ \Delta AGR \end{bmatrix} \tag{6}$$

Error correction equation is expressed in: $\mathrm{EC}_{it} = \sum_{j=1}^{p} \delta_{1j} \ln CO_{t-j} + \sum_{j=1}^{q} \beta_{ij} X'_{i,t-j} + \varepsilon_{it}$

Where ϕ_i is the coefficient of error correction term that measures the speed of adjustment towards equilibrium; Δ is the first difference operator; j is the time lag; EC_{it} is the error correction term. The lag selection for this study is determined using the Akaike information criterion (AIC) test.

Subsequently, the Wald test is conducted to examine the significance of the interaction term parameter in the model. The t-statistics, F-statistic, and Chi-square statistics test the null hypothesis (H0) that the interaction term does not impact the equation. On the other hand, if the alternative hypothesis (H1) is supported, it indicates that the interaction term plays a significant role in the model. Thus, the Wald test of coefficient evaluates if the EKC model should include the interaction term.

Results and Discussion

Table 2 shows a cross-sectional dependency analysis. The Breusch-Pagan LM test, Pesaran scaled test, and Pesaran CD test reject the null hypothesis of cross-sectional independence at the significance levels of 1% and 10%, respectively, suggesting the presence of cross-sectional dependence.

Table 2. Cross-sectional Dependency Test

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	400.7957***	36	(0.000)
Pesaran scaled LM	42.991***		(0.000)
Pesaran CD	-1.678*		(0.093)

Notes: Standard errors in parentheses, *** and ** indicated statistically significant at 1%, and 5%, respectively.

Table 3 presents the results of four-panel unit root tests (LLC, IPS, PP-Fisher, and ADF-Fisher). The test statistics for all variables are not statistically significant, indicating that the null hypothesis of non-stationarity is accepted for all variables. However, after performing the first difference, the test statistics for all variables become statistically significant at the 1% level, suggesting that most series are integrated of first order (1).

Table 3. Results from Panel Unit Root Test

Test	Variables	Level	First Difference
Levin, Lin, and Chu	Carbon Dioxide	1.537	-6.395***
	Industrialization	-0.171	-8.410***
	Renewable energy	-3.612***	-9.544***
	Gross Domestic Product	0.216	-9.195***
	Trade Openness	-0.399	-7.850***
	Agriculture	-1.303*	-2.711***
Im, Pesaran and Shin W-Stat	Carbon Dioxide	3.718	-6.997***
	Industrialization	2.457	-8.088***
	Renewable energy	-3.264***	-10.63***
	Gross Domestic Product	2.921	-8.017***
	Trade Openness	-4.009***	-12.406***
	Agriculture	-0.966	-7.335***
ADF Fisher Chi-square	Carbon Dioxide	15.47	105.08***
	Industrialization	7.908	98.493***
	Renewable energy	56.841***	127.628***
	Gross Domestic Product	4.756	96.206***
	Trade Openness	55.045***	152.239***
	Agriculture	28.223*	95.462***
PP Fisher Chi-square	Carbon Dioxide	33.106**	122.761***
	Industrialization	7.439	114.346***
	Renewable energy	41.526***	154.524***
	Gross Domestic Product	4.358	101.389***
	Trade Openness	18.299	139.774***
	Agriculture	43.816***	160.006***

Notes: Standard errors in parentheses, *** and ** indicated statistically significant at 1%, and 5%, respectively.

Table 4 presents the outcomes of the Kao panel cointegration analysis. The test statistic estimate from the Kao test is statistically significant at the 1% level. These findings demonstrate that panel cointegration tests reject the null hypothesis, indicating that the estimated model exhibits cointegration for all three specifications.

Table 4. Results of the Kao Residual Cointegration

Test Statistic	t-Statistic	Prob.
ADF	-3.435***	(0.000)

Notes: Standard errors in parentheses, *** and ** indicated statistically significant at 1%, and 5%, respectively.

Long-run and short-run estimation in ASEAN

In this section, we present the long-term elasticity estimates of CO2 emissions concerning industrialization, renewable energy, moderating variables of industrialization and renewable energy, and GDP per capita. The PMG-ARDL model estimation in Table 5 is the basis for these computations, with all variables estimated in their natural logarithm form.

The results in Table 5 indicate that, in ASEAN, all coefficient signs have results aligned with the hypothesis. Most variables present statistical significance at the 1% level, except for GDP, which is statistically significant at the 10% level. The negative significant coefficient of $\ln IND$ and the positive sign of $\ln IND^2$ provide evidence ofprovide Environmental Kuznets Curve (EKC) of industrialization in ASEAN. This result suggests that carbon emissions per capita increase with industrialization, but beyond a certain level of industrialization (the turning point), they begin to decrease.

In the long run, the share of renewable energy reduces the percentage of carbon emissions per capita, as indicated by the negative coefficient on both RE and $ln(IND) \cdot RE$. Additionally, GDP per capita contributes to increase in emissions where a 1% increase in GDP per capita leads to a 0.2% increase in carbon emissions per capita.

Table 5. ARDL Estimation

Variable	Coefficient	Std. Error
Long Run Equation		
$\ln IND$	1.325***	0.153
$\ln IND^2$	-0.031***	0.003
RE	-0.010*	0.006
$\ln IND \cdot RE$	-0.002***	0.000
$\ln GDP$	0.203***	0.018
AGR	-0.019***	0.002
OPN	-0.004***	0.000
Short Run Equation		
$COINT$	-0.341	0.264
$\Delta \ln CO$ (-1)	-0.008	0.214
$\Delta \ln CO$ (-2)	-0.019	0.144
$\Delta \ln CO$ (-3)	-0.038	0.150
$\Delta\, lnIND$	-5.613**	2.706
$\Delta\, lnIND$(-1)	-2.088	2.838
$\Delta\, lnIND^2$	-0.114**	0.054
$\Delta\, lnIND^2$ (-1)	-0.045	0.068
$\Delta\, RE$	-11.400	15.214
$\Delta\, RE$(-1)	-39.449	37.387
$\Delta \ln IND \cdot RE$	-0.363**	0.521
$\Delta \ln IND \cdot RE$(-1)	-1.811**	1.725
$\Delta \ln GDP$	-0.095	0.191
$\Delta \ln GDP$ (-1)	-0.149	0.206
$\Delta\, AGR$	-0.101	0.070
$\Delta\, AGR$ (-1)	-0.042	0.091
$\Delta\, TRD$	-0.001	0.000
$\Delta\, TRD$ (-1)	-0.001	0.000
C	-4.096	3.154

Notes: Standard errors in parentheses, *** and ** indicated statistically significant at 1%, and 5%, respectively. Model selection method: Akaike info criterion (AIC).

Notably, a 1% increase in OPN and the share of AGR corresponds to a 0.4% and 1.9% rise in carbon emissions per capita, respectively. Based on previous research, Nathaniel (2021) demonstrates that the effect of trade on ecological footprint differs in the long and short term. International trade worsens environmental degradation in the short run but not in the long run. This effect suggests that trade provides emerging economies access to environmentally friendly technologies over time. Aside from the fact that trade activities magnify the transition from a pre-industrial economy to an industrialized economy, these findings validate the Technology Spillover Effect. Trade liberalization plays a pivotal role in facilitating the transfer of advanced technology from technology-exporting countries to technology-importing countries, leading to enhanced productivity and improved CO2 emission performance on a global scale (Du & Li, 2019).

Research conducted by the Food and Agriculture Organization (FAO) suggests that the agricultural sector has significant potential to reduce global emissions by 20-60% by 2030 through reduced deforestation and increased renewable energy generation (Liu et al., 2017). Agriculture's promotion of renewable energy development and CO2 emission reduction holds promise for mitigating the impacts of global warming and climate change (Appiah et al., 2021)

In the short run, the estimated coefficient for ECT is negative and statistically significant, indicating the presence of a long-run equilibrium relationship among the series. Moreover, variables of $RE, \ln GDP, AGR,$ and OPN are not statistically significant in this panel. The findings regarding industrialization in the short run align with the long-run results, demonstrating the existence of the inverted U-shaped Environmental Kuznets Curve (EKC) (Table 6). This finding confirms that in the early stage of industrialization, the increase of value added by an industry to the GDP will increase carbon emissions. After reaching the peak, the increase in the industry will reduce emissions.

The investigation into causality among the variables reveals evidence of a relationship between the value added by the industry and CO2 emissions in both the short and long run. Previous studies, such as the one conducted by Gillani and Sultana (2020) on selected ASEAN countries, have also tested the EKC framework. Their findings support the EKC theory, showing a negative effect of GDP and a positive effect of GDP square on the relationship.

Table 6. EKC Hypothesis in Long- and Short-run ASEAN Countries

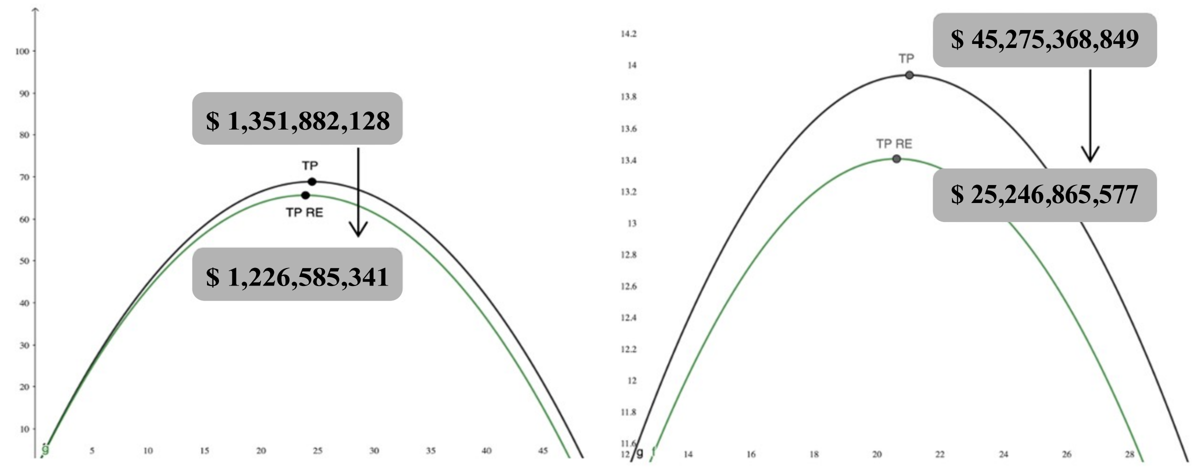
	Coefficient of $\ln IND$		Coefficient of $\ln IND^2$		Results
Long Run	1.325	$\beta_1>0$	-0.031	$\beta_2<0$	Inverted-U shaped relationship
Short Run	5.613	$\beta_1>0$	-0.114	$\beta_2<0$	Inverted-U shaped relationship

Turning point of Environment Kuznets Curve in ASEAN

Calculating the EKC's turning point at zero renewable energy scores is observed at $1,351,882,128 in the long run and $45,275,368,849 in the short run. However, considering ASEAN countries' average renewable energy consumption rate, the EKC's peak turning point reaches $1,226,585,341 in the long run and $25,246,865,577 in the short run. These findings suggest that a growth in industrialization, accompanied by a greater dependency on renewable energy, reduces emissions, resulting in a faster shift of the turning point of the Environmental Kuznets Curve (EKC) compared to the EKC without considering renewable energy.

Our findings aligned with previous studies, such as Dargahi and Khameneh (2019) and Tang et al. (2020). These findings highlight the potential for economic growth to be significantly enhanced by reducing pollution levels and adopting improved technologies, contributing to the overall environmental quality in ASEAN countries. Moreover, technological advancements also promote the adoption of alternative energy sources and renewable energy production, fostering the expansion of the secondary, tertiary, and services sectors, all of which help to mitigate carbon emissions (Kaika & Zervas, 2013).

The EKC hypothesis posits that improving the environment involves replacing outdated and polluting technologies with new and cleaner ones, representing the technique effect of economic growth. As a result, using renewable energy is considered crucial, as it is seen as an effective means of reducing CO2 emissions by advancing clean technologies. The interaction factors might mitigate industrialization's impact on CO2 emissions. Given the enormous potential for ASEAN industrialization to develop clean energy sources, which may accelerate its industry sector to improve its environmental performance, the focus is renewable energy. Numerous studies have demonstrated that renewable energy consumption may dramatically reduce carbon emissions, but few have explained how this may influence the EKC's turning point.



Long-run Estimation EKC in ASEAN Short-run Estimation EKC in ASEAN

Figure 4. Long-run and Short-run Estimation Environmental Kuznet Curve (EKC) in ASEAN

Figure 4 illustrates our results that encouraging renewable energy consumption can hasten EKC's transition to its turning point. Increasing renewable energy may accelerate the EKC's turning point, lowering carbon emissions. Therefore, a nation (or group of nations) can accelerate the EKC's tipping point by boosting renewable energy usage. It presents a possible response to the issue of whether the shift in energy consumption caused by the growth of renewable energy is a crucial element influencing the EKC tipping point.

Short-run country-specific in ASEAN member state

Varied outcomes regarding the Environmental Kuznets Curve (EKC) hypothesis among ASEAN member states have been observed. The results indicate that the EKC exists in most ASEAN countries, including Brunei, Cambodia, Laos, Myanmar, Malaysia, Singapore, and Thailand, as evidenced by the confirmation of an inverted U-shaped curve. However, the EKC hypothesis does not hold in the case of Indonesia and the Philippines. Considering the coefficient of $\beta 1 < 0$, it is possible to say that the EKC relationship of industrialization and emission has a U-shaped relationship.

Several works of literature have also validated these varied results of the EKC hypothesis in ASEAN member states. In the case of the Philippines and Indonesia, Saboori & Sulaiman (2013) indicate that Indonesia and the Philippines remain in the growing portion of the carbon Kuznets curve. Due to the varying levels of economic development among ASEAN countries and the unequal distribution of economic progress across the region, diverse outcomes are expected. From 1970 to 2013, Liu et al. (2017) discovered that the estimates do not substantiate the existence of the inverted U-shaped Environmental Kuznets Curve (EKC) in particular ASEAN countries, including Indonesia, the Philippines, and Thailand.

Similar findings were reported by Chandran and Tang (2013), who also found no evidence supporting the EKC for several ASEAN member states. Notably, some countries within ASEAN, such as Indonesia and the Philippines, are experiencing the emergence of a new consumer class driven by rising incomes. As consumer spending per capita increases, these factors have pushed demand to intensify their industry sectors to cope with the region's advancement. Moreover, there are serious efforts to increase their renewable energy consumption despite the predominantly emission-intensive industry, especially manufacturing, which demands electricity and extensive heat.

Examining the role of renewable energy in addressing environmental degradation in ASEAN countries, Table 8 computes the turning point of the Environmental Kuznets Curve (EKC) hypothesis. While the previous section provided results for ASEAN as a whole, inconsistent findings are evident when analyzing each country individually.

Table 7. EKC Hypothesis in ASEAN Countries (Short-run)

Countries	Coefficient of $\ln IND$		Coefficient of $\ln IND^2$		Results
Brunei	6.864	$\beta_1 > 0$	-0.158	$\beta_2 < 0$	Inverted-U shaped relationship
Indonesia	-3.5631	$\beta_1 < 0$	0.070	$\beta_2 > 0$	U-shaped relationship
Cambodia	14.673	$\beta_1 > 0$	-0.348	$\beta_2 < 0$	Inverted-U shaped relationship
Laos	16.214	$\beta_1 > 0$	-0.289	$\beta_2 < 0$	Inverted-U shaped relationship
Myanmar	7.3477	$\beta_1 > 0$	-0.089	$\beta_2 < 0$	Inverted-U shaped relationship
Malaysia	4.304	$\beta_1 > 0$	-0.040	$\beta_2 < 0$	Inverted-U shaped relationship
Philippines	-15.636	$\beta_1 < 0$	0.313	$\beta_2 > 0$	U-shaped relationship
Singapore	16.650	$\beta_1 > 0$	-0.321	$\beta_2 < 0$	Inverted-U shaped relationship
Thailand	4.378	$\beta_1 > 0$	-0.080	$\beta_2 < 0$	Inverted-U shaped relationship

The moderating effect of renewable energy in industrialization in Myanmar, Singapore, Cambodia, Laos, and Malaysia reduces the EKC's turning point. These findings align with the predictions made by Nathaniel and Khan (2020) and Zeraibi et al. (2021), supporting the notion that renewable energy contributes to lower ecological footprints in the Philippines, Singapore, and Malaysia. Singapore serves as an illustrative example, where Nathaniel and Khan (2020) assert that the environmental impact of economic expansion is minimized due to the country's reliance on natural gas instead of coal for energy generation. This strategic decision has resulted in reduced emissions associated with economic growth. Additionally, the nation is more aggressive than other ASEAN members in combating climate change by acquiring clean technology and constructing infrastructures.

Table 8. Turning point for EKC Hypothesis

Short-run Country Specific	EKC of Industrialization in billion US $	EKC of Industrialization with Renewable Energy in Billion US $	Results
Brunei	2,559.467	2,634.887	Increasing
Cambodia	1,411.662	1,407.920	Decreasing
Laos	4,929.951	3,130.602	Decreasing
Myanmar	1,948.935	1,931.287	Decreasing
Malaysia	82,523.523	48,894.278	Decreasing
Singapore	32,058.865	31,795.514	Decreasing
Thailand	68,637.478	78,914.608	Increasing

Brunei and Thailand's estimation shows that despite the indirect effect of renewable energy in industrialization, these countries adjusted turning point increases. Value-added industries with more renewable energy produce more carbon emissions at this region's early stages of economic development. Similar to the findings for Thailand, as indicated by Vo et al. (2019), this study also suggests that the current level of renewable energy usage in ASEAN countries might need to be revised to mitigate CO2 emissions effectively. Furthermore, renewable energy has a limited impact on reducing environmental degradation. However, Gill et al. (2018) argue that a shift towards less polluting renewable energy sources could significantly accomplish sustainable development objectives.

Impact of renewable energy on industrialization sectors towards emissions in ASEAN

The industry's value added to GDP derived from 2019 encompasses industrialization's short-term and long-term impact. Similarly, renewable energy data was obtained from the percentage of renewable energy consumption in 2019. Table 9 illustrates the relationship between industrialization and renewable energy concerning carbon emissions in ASEAN, as estimated through short and long-run elasticity analysis. Deriving from our previous results in PMG-ARDL estimation, the short-run elasticity is explained as follows:

$$\frac{\%\,CO}{\%\,IND} = 5.613 + 2 \times -0.114 \ln IND - 0.363RE$$

and the long-run elasticity is described through:

$$\frac{\%\,CO}{\%\,IND} = 1.325 + 2 \times -0.031 \ln IND - 0.002RE$$

Table 9. Elasticity of Industrialization and Renewable Energy to CO2 in ASEAN

Countries	Results (%) in Short-run	Results (%) in Long-run
Brunei	-0,75	-0,12
Indonesia	-1,67	-0,37
Cambodia	-0,78	-0,13
Laos	-0,70	-0,10
Myanmar	-1,01	-0,19
Malaysia	-1,38	-0,30
Philippines	-1,34	-0,28
Singapore	-1,31	-0,27
Thailand	-1,47	-0,31

Table 9 projects the short-run elasticity of industrialization to the share of renewable energy consumption in carbon dioxide emissions per capita for each ASEAN country in 2019. We can conclude that assuming ceteris paribus, every 1% increase in industrialization will reduce carbon dioxide per capita by 0.75% in Brunei, 1.67% in Indonesia, 0.78% in Cambodia, 0.70% in Laos, 1.01% in Myanmar, 1.38% in Malaysia, 1.34% in the Philippines, 1.31% in Singapore, 1.47% in Thailand.

The third column of Table 9 shows the long-run estimation of the elasticity of value added from the industry concerning the share of renewable energy consumption in carbon dioxide emissions per capita for each ASEAN country in 2019. Every 1% increase in industrialization will reduce carbon dioxide per capita by 0.12% in Brunei, 0.37% in Indonesia, 0.13% in Cambodia, 0.1% in Laos, 0.19% in Myanmar, 0.3% in Malaysia, 0.28% in the Philippines, 0.27% in Singapore, 0.31% in Thailand. Based on both short-run and long-run analyses, it is confirmed that the share of renewable energy mitigates the impact of industrialization on carbon dioxide emissions per capita. This observation suggests a structural shift in the industry, with technological advancements and stricter environmental regulations aligning with growing environmental consciousness. Moreover, regarding renewable energy consumption, industrialization negatively influences carbon dioxide emissions. In the early phases of industrialization, many nations pursued high GDP development and supported industrialization by using vast quantities of fossil fuels. As industrialization reaches significant levels, there is a concerted effort to phase out or incentivize industries with high pollution levels and energy consumption, encouraging their transition towards adopting renewable and clean energy sources.

Consequently, the favorable impact of industrialization on carbon dioxide emissions has diminished at this point. In addition, industrialization has always profited from technical advancements, such as the enhancement of industrial output and energy technology development. During industrialization, these have reduced reliance on fossil fuels to some extent, as shown by the elasticity from our finding in Table 9.

The effectiveness of implementing the EKC is highly dependent on the comparative resource advantages of each country. The expectation is for countries to specialize in resource-intensive production while adhering to environmentally friendly regulations. However, a concerning trend emerges where developed countries shift the impact of environmental pollution to developing nations. Strengthening international cooperation in energy and environmental sustainability is urgent regarding this issue. This action involves a commitment from each country to foster environmental sustainability through various innovations, such as technology transfer, which can promote sustainable development across the globe.

Post Estimation Wald Test for Interaction Variable

The Wald test of coefficient restriction was employed to assess the necessity of including the interaction term $(\ln IND \cdot RE)$ in this study (see Table 10). As indicated by the t-statistics, F-statistic, and Chi-square statistics, the results reject the null hypothesis (H0). This supports the inclusion of the interaction term in the EKC model for the current research.

Table 10. Wald Test Results

Test Statistic	Value	Degree of Freedom	Probability
t-statistic	-6.0696	92	0.000
F-statistic	36.841	(1, 92)	0.000
Chi-square	36.841	1	0.000

Notes: Standard errors in parentheses, *** and ** indicated statistically significant at 1%, and 5%, respectively.

Conclusion

This study examines industrialization, renewable energy, and carbon emissions in nine ASEAN nations from 1990 to 2019. PMG-ARDL provides for short-run dynamics throughout the sample panel's cross-sectional units. Incorporating industry and renewable energy departs from the EKC framework. Short-run and long-term tests show that ASEAN has industrialized EKC. Renewable energy also mediates industry-CO2 emissions. We found that switching to renewable energy can reduce ASEAN industrialization's environmental impact—Brunei, Laos, Myanmar, Malaysia, Singapore, and Thailand. EKC is absent in the Philippines and Indonesia in the short term, though not statistically significant. The studies show that Indonesia and the Philippines are still growing on the carbon Kuznets curve. This varied outcome is expected since the nine ASEAN nations analyzed are at different economic stages.

We also find that renewable energy can move the turning point of CO2 emissions per capita in Cambodia, Laos, Myanmar, the Philippines, Singapore, and Malaysia, but not Brunei and Thailand, by reducing industrialization in each ASEAN state. As most ASEAN may minimize the EKC curve's turning point, renewable energy can mitigate industrialization's environmental effect. This analysis also estimates industry and renewable energy consumption elasticity by estimating per capita carbon dioxide emissions. Industrialization will cut carbon dioxide per capita in all ASEAN nations in the short and long term. It also shows that renewable energy cuts industrialization's direct carbon dioxide emissions.

This study should have added other variables and expanded the observation period. Therefore, future research could examine the impact of factors like human capital, population dynamics, and foreign direct investment (FDI) on explaining carbon emissions, along with investigating the drivers impacting the adoption of renewable energy in another region. Also, we acknowledge that spatial autocorrelation might occur in this issue. Thus, further study might consider this matter to complete these findings and provide more appropriate and practical policy recommendations.

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