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The Role of Economic Growth in Moderating the Impact of Energy Consumption on Carbon Emissions in ASEAN-5

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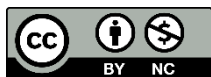
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Abstract

The ASEAN-5 countries (Indonesia, Malaysia, the Philippines, Singapore, and Thailand) have experienced rapid economic growth, leading to increased energy consumption and carbon emissions. While economic expansion initially increases emissions, it can also facilitate the adoption of cleaner energy sources. This study investigates the moderating role of economic growth in the impact of energy consumption on carbon emissions using panel data from 2001 to 2022. The Autoregressive Distributed Lag (ARDL) method was employed due to its capacity to analyze both short- and long-term relationships. The results from the ARDL analysis reveal that the consumption of non-renewable energy substantially elevates carbon emissions in both the short and long term. In contrast, the influence of renewable energy consumption on emissions is positive only in the long term. Additionally, non-renewable energy consumption exerts a positive effect on CO₂ emissions, which is moderated by both economic growth and the square of economic growth. Conversely, renewable energy consumption contributes negatively to CO₂ emissions, similarly moderated by economic growth and its square. These findings correspond with the Environmental Kuznets Curve (EKC) theory, which posits that emissions initially rise alongside economic development, only to subsequently decrease as economies shift towards more sustainable technologies. Therefore, policymakers are advised to implement robust environmental regulations, invest in renewable energy initiatives, and promote sustainable economic practices to achieve long-term carbon reduction goals. Moreover, governments should enforce stricter policies on fossil fuel consumption and raise public awareness of environmental preservation.



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1. Introduction

The Association of Southeast Asian Nations (ASEAN) economies have demonstrated remarkable economic growth in recent decades, characterized by the expansion of manufacturing sectors, population growth, and increased urbanization [1, 2]. Economic development in these countries, which comprise the ASEAN-5 group, including Indonesia, Malaysia, the Philippines, Singapore, and Thailand, frequently leads to increased energy

demand driven by industrial growth, transportation needs, and residential consumption [3, 4]. Notably, the transition toward more industrialized economies is often accompanied by a rise in fossil fuel consumption, including coal, oil, and natural gas, which are significant contributors to carbon emissions [5, 6]. For instance, Indonesia's GDP growth has averaged around 5–6% annually, while Malaysia's GDP growth has been around 4–5% annually. The Philippines has seen strong growth of

6–7% annually over the past decade. Thailand's GDP growth has ranged from 3–4% in recent years. Singapore's economy is highly developed, with a GDP of approximately USD 486 billion in 2022 and a per capita GDP of USD 69,000, and it has grown at an average rate of 3–4% in recent years [7].

However, economic growth exhibits a dual effect on carbon emissions. While heightened economic activity may initially result in increased emissions, it can also provide the resources and infrastructure needed to support the adoption of sustainable energy solutions and enhance energy efficiency. Consequently, the correlation between economic growth and carbon emissions is non-linear, influenced by factors such as energy policy, technological development, and consumer behavior [8, 9]. For instance, Singapore's highly developed economy has adopted energy-efficient technologies and has made significant investments in clean energy [7].

The Environmental Kuznets Curve (EKC) hypothesis posits that as an economy progresses, environmental degradation initially intensifies but subsequently improves after reaching a certain level of income or economic development [10]. In summary, at lower levels of economic development, industrialization has been shown to increase pollution levels. However, as nations achieve higher income levels, they may develop the capacity to implement policies and technologies that reduce pollution and carbon emissions [11]. The EKC suggests that the relationship between economic growth and environmental impact follows an inverted U-shaped curve [12, 13]. This theory may be applicable to the five countries that comprise the ASEAN-5, where the initial stages of economic growth are marked by elevated energy consumption and emissions [14, 15]. Nonetheless, the early phases of development may result in a decrease in emissions by embracing more environmentally friendly technologies. Singapore serves as a notable example of this phenomenon, where economic growth has driven substantial investments in energy-efficient technologies and renewable energy sources, resulting in reduced carbon emissions per unit of GDP despite a high level of industrialization [16].

The green growth theory posits that economic growth and environmental sustainability can coexist if countries invest in green technologies, energy efficiency, and sustainable practices [17, 18]. This approach emphasizes that achieving economic prosperity does not require excessive consumption of natural resources or environmental harm [17, 18]. The theory suggests that, with appropriate investments, economic growth can be achieved while reducing environmental impact. For the five countries that comprise the ASEAN-5, adopting green

growth strategies has the potential to mitigate the adverse effects of economic expansion on carbon emissions. This can be achieved by investing in renewable energy sources, low-emission infrastructure, and eco-friendly industrial methods [19–22]. Thailand's initiatives to broaden its energy portfolio by incorporating renewable resources like solar and biomass into its energy sector exemplify an attempt to balance economic growth with environmental sustainability [23].

Energy consumption patterns in the ASEAN-5 countries are shaped by economic and social factors. Demand is primarily driven by the industrial, transportation, and residential sectors [15, 24]. However, the extent of energy consumption varies significantly across these nations, influenced by income levels, urbanization, and the availability of energy infrastructure [15, 24]. Higher per capita energy consumption is generally associated with larger carbon footprints, particularly when the energy mix is heavily reliant on fossil fuels. For instance, in 2021, Indonesia's carbon emissions from energy use amounted to approximately 1,028 MtCO₂, while Singapore emitted around 51 MtCO₂ [25]. Singapore has made significant investments in energy efficiency and clean energy solutions, whereas countries like Indonesia and the Philippines have faced challenges related to energy access, infrastructure, and dependence on coal [26]. Additionally, energy consumption patterns in these nations are shaped by cultural practices, political frameworks, and societal attitudes toward sustainability.

As economies grow, they often invest in efficient technologies, renewable energy, and sustainable infrastructure, which can decouple energy use from carbon emissions. Singapore exemplifies this trend with an energy intensity of just 0.14 kWh/USD, reflecting its high-tech economy and energy-efficient infrastructure [25]. Similarly, economic growth in ASEAN-5 nations can support environmental policies such as carbon taxes, energy efficiency standards, and clean energy investments [27]. It also enhances the government's capacity to subsidize low-carbon transitions and encourage sustainable practices. For example, Singapore introduced a carbon tax of SGD 5 per ton of CO₂, set to rise by 2030 [28].

Furthermore, economic growth plays a crucial role in moderating the relationship between energy consumption and emissions by promoting energy efficiency and the adoption of low-carbon technologies. For instance, energy-efficient appliances, electric vehicles, and smart grid technologies can reduce the carbon intensity of energy consumption even as economic activity continues to rise [25]. While economic growth often leads to increased energy consumption, it

Table 1. Operational definition of variables and data sources.

Variable Type	Variable	Description	Units	Sources
Dependent	CO2	Amount of carbon dioxide emissions released into the atmosphere.	Kilotons	World Development Indicators [7]
Independent	NREC	Total consumption of non-renewable energy, including oil, gas, and coal.	Kilojoules	Energy Institute [29]
	REC	Total consumption of renewable energy from hydropower, solar, wind, and biofuels.	Kilojoules	Energy Institute [29]
Moderator	GROWTH	Annual percentage change in Gross Domestic Product (GDP).	Percent (%)	World Development Indicators [7]
	GROWTH ²	The square value of GROWTH.	Percent (%)	Authors' own calculation

can also provide the necessary resources to mitigate the environmental impact of energy use [21, 30, 31]. The extent to which economic growth moderates the link between energy consumption and carbon emissions in these nations depends on various factors, including policy decisions, technological advancements, and consumer behavior. Tackling these issues necessitates a well-rounded strategy that promotes sustainable economic development while minimizing the carbon emissions associated with energy use [32–34]. The EKC, decoupling, and green growth strategies illustrate how economic growth can align with environmental sustainability, provided that the ASEAN-5 countries implement appropriate measures [35].

Recent studies by Lean et al. [36], Saboori et al. [37], Vo et al. [5], Munir [38], and Tran et al. [39] have demonstrated a statistically significant relationship between energy consumption, economic growth, and CO₂ emissions in ASEAN. Bildicri [40] identified a significant causal relationship between these variables using Granger causality. Wang et al. [41] found that energy consumption negatively impacts life expectancy, primarily due to environmental degradation. Syahril et al. [42] observed that, in the short term, CO₂ emissions are significantly influenced by energy consumption, economic growth, and energy resources, while in the long term, economic growth and energy resources remain the key factors. Amalina et al. [30] found that economic growth reduces carbon emissions while energy consumption increases them, both with statistical significance. However, the quadratic model suggests that the EKC does not apply to Indonesia. The impact of energy consumption is categorized into two types: non-renewable and renewable energy, each affecting CO₂ emissions differently. Several researchers, including Wang et al. [41], Idroes et al. [43], and Kartal et al. [44], have found that non-renewable energy sources contribute to environmental degradation. In contrast, studies by Raihan et al. [8], Li et al. [45], and Koc & Bulus [46] indicate that renewable energy reduces CO₂ emissions and improves environmental quality. Given these findings, researchers have taken a fresh approach

to studying this issue, distinguishing their work from previous studies. They examined how economic growth moderates the impact of energy consumption on carbon emissions, analyzing both short- and long-term relationships.

The objective of this study is to address these knowledge gaps by examining the moderating effect of economic growth on the relationship between energy consumption patterns and carbon emissions in the ASEAN-5 region from 2001 to 2022. The study provides a comprehensive analysis of this dynamic using Autoregressive Distributed Lag (ARDL) to assess the impact of energy consumption and economic growth on CO₂ emissions. By addressing these gaps, this research aims to inform more effective policymaking and contribute to the global discourse on sustainable development in the ASEAN-5.

2. Materials and Methods

2.1. Data and Variables

This study employs panel data from 2001 to 2022 for the ASEAN-5 countries: Indonesia, Malaysia, the Philippines, Singapore, and Thailand. The selection of these countries and this time frame is justified by their significant economic growth, rising energy consumption, and increasing carbon emissions since the 2000s. Additionally, data availability for the research variables is more comprehensive in these five countries. This study examines how economic growth moderates the effect of energy consumption on CO₂ emissions. All detailed variables, including their types, descriptions, units, and sources, are presented in detail in Table 1.

CO₂ emissions serve as the dependent variable in this study, while non-renewable energy consumption (NREC) and renewable energy consumption (REC) act as independent variables. Economic growth (GROWTH) and its squared term (GROWTH²) function as moderator variables [47]. Except for GROWTH and GROWTH², all variables are log-transformed to facilitate interpretation and linearize relationships in regression models [48, 49]. Since GROWTH and GROWTH² are already in percentage form, log transformation is unnecessary, preventing

issues with undefined values for zero or negative numbers. Log transformation is primarily applied when data is highly skewed or has a limited range [50]. Additionally, this study does not include control variables due to potential multicollinearity concerns, which could distort regression estimates and obscure key relationships [51, 52]. Given economic theories like the EKC, economic growth is directly linked to carbon emissions, and adding control variables might dilute the study's focus [10]. Moreover, in many developing regions, including ASEAN-5, data on control variables such as technological advancements or policy implementation is often incomplete or inconsistent, potentially leading to biased estimates or reduced sample sizes [53].

The inclusion of economic growth and its squared term as moderator variables allows for an analysis of how energy consumption influences carbon emissions at different stages of growth. Initially, economic expansion may promote cleaner energy use and efficiency, whereas higher growth rates may lead to increased reliance on fossil fuels, exacerbating emissions [54]. The squared term captures potential non-linear effects, revealing whether the relationship between economic growth and carbon emissions changes at different growth levels. By incorporating both variables as interaction terms, the model captures the shifting dependence of emissions on energy consumption across varying economic conditions, providing a more comprehensive and realistic depiction of this relationship [55].

2.2. Conceptual Framework

Figure 1 illustrates the relationships between economic growth, energy consumption (renewable and non-renewable), and carbon emissions (CO₂). It highlights how different energy consumption patterns contribute to emissions and the moderating role of economic growth. Non-renewable energy use, particularly fossil fuel combustion, is a major source of CO₂ emissions, creating a positive correlation between the two. In contrast, renewable energy sources like solar, wind, and hydropower produce minimal direct emissions, leading to a negative correlation between renewable energy consumption and overall carbon emissions. The role of economic growth in shaping the impact of energy consumption patterns is crucial. Traditionally, economic expansion has driven higher energy demand, often increasing reliance on non-renewable sources and elevating carbon emissions. However, growth can also spur investment in renewable energy, facilitating a shift toward cleaner alternatives. The overall effect of economic growth on carbon emissions depends on the balance between renewable and non-renewable energy use. While growth may intensify environmental strain

through higher emissions, it also creates opportunities for sustainable energy development that can help mitigate these effects.

2.3. Empirical Model and Estimation Approach

2.3.1. Dynamic Approach with Autoregressive Distributed Lag (ARDL)

This study employs the ARDL model to analyze the short- and long-term relationships between economic growth, energy consumption, and carbon emissions. The ARDL approach is particularly useful for examining both stationary and non-stationary time series data, allowing for robust analysis even when variables exhibit different orders of integration [56]. The initial stages of the ARDL methodology involve pre-estimation tests, including stationarity tests, optimal lag selection, and cointegration tests, which ensure the validity of the model estimation [21, 57]. Given that many macroeconomic variables, including energy consumption and economic growth, often exhibit unit roots, failing to account for their non-stationarity can lead to spurious regression results. Therefore, conducting these preliminary tests is essential to obtaining reliable estimations.

The ARDL method allows for the assessment of the relationship between independent and dependent variables in both the short and long run. The general econometric function representing the model is given in Equation 1.

$$CO_2 = f(NREC, REC, GROWTH, NREC * GROWTH, REC * GROWTH, NREC * GROWTH^2, REC * GROWTH^2) \quad (1)$$

CO₂ represents carbon emissions, NREC denotes non-renewable energy consumption, and REC signifies renewable energy consumption. GROWTH and GROWTH² represent economic growth and economic growth squared, acting as moderators. The model is further divided from Equation 1 into separate equations: the NREC model for non-renewable energy in Equation 2 and the REC model for renewable energy in Equation 3.

$$CO_2 = f(NREC, GROWTH, NREC * GROWTH, NREC * GROWTH^2) \quad (2)$$

$$CO_2 = f(REC, GROWTH, REC * GROWTH, REC * GROWTH^2) \quad (3)$$

To observe the growth moderation between the effects of non-renewable and renewable energy consumption on carbon emissions, the equation model derived from the basic theory of the EKC is modified, resulting in Equation 4 for the NREC model and Equation 5 for the REC model.

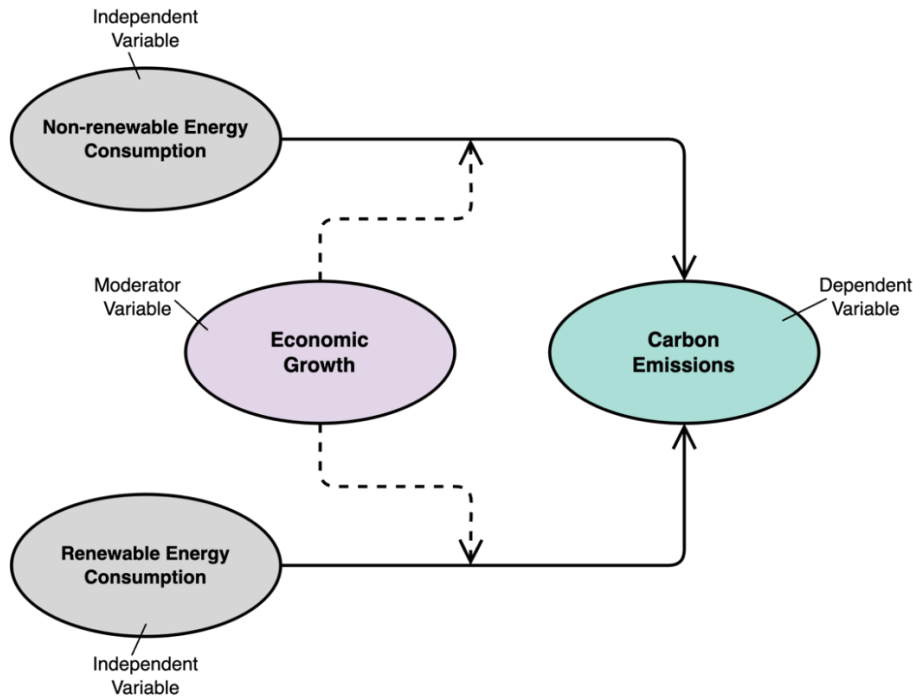


Figure 1. Conceptual framework.

$$CO2_{it} = \beta_{11} + \beta_{12} \ln NREC_{it} + \beta_{13} GROWTH_{it} + \beta_{14} \ln NREC * GROWTH_{it} + \beta_{15} \ln NREC * GROWTH^2_{it} + \varepsilon_{it} \quad (4)$$

$$CO2_{it} = \beta_{11} + \beta_{12} \ln REC_{it} + \beta_{13} GROWTH_{it} + \beta_{14} \ln REC * GROWTH_{it} + \beta_{15} \ln REC * GROWTH^2_{it} + \varepsilon_{it} \quad (5)$$

Based on Equations 4 and 5, the ARDL model for NREC and REC is shown in Equations 6 and 7. Where CO₂ represents carbon emissions, NREC denotes non-renewable energy consumption, and REC signifies renewable energy consumption. GROWTH and GROWTH²

capture economic growth and its squared term, respectively. The interaction between economic growth and non-renewable energy consumption is represented by *NREC * GROWTH*, while *REC * GROWTH* reflects the interaction between economic growth and renewable energy consumption. Additionally, *NREC * GROWTH²* and *REC * GROWTH²* account for the quadratic moderation effects of economic growth on different energy consumption types. Δ represents inertia (lag), β₁–β₅ corresponds to short-term dynamic relationships, and φ₁–φ₅ captures long-term dynamics. The Error

$$\Delta \ln CO2_{n,t} = \beta_0 + \sum_{i=1}^n \beta_1 \Delta \ln CO2_{n,t-i} + \sum_{i=1}^n \beta_2 \Delta \ln NREC_{n,t-i} + \sum_{i=1}^n \beta_3 \Delta GROWTH_{n,t-i} + \sum_{i=1}^n \beta_4 \Delta \ln NREC * GROWTH_{n,t-i} + \sum_{i=1}^n \beta_5 \Delta \ln NREC * GROWTH^2_{n,t-i} + \psi ECT_{n,t-1} + \phi_1 \ln CO2_{n,t-1} + \phi_2 \ln NREC_{n,t-1} + \phi_3 GROWTH_{n,t-1} + \phi_4 \ln NREC * GROWTH_{n,t-1} + \phi_5 \ln NREC * GROWTH^2_{n,t-1} + \varepsilon_{n,t} \quad (6)$$

$$\Delta \ln CO2_{n,t} = \beta_0 + \sum_{i=1}^n \beta_1 \Delta \ln CO2_{n,t-i} + \sum_{i=1}^n \beta_2 \Delta \ln REC_{n,t-i} + \sum_{i=1}^n \beta_3 \Delta GROWTH_{n,t-i} + \sum_{i=1}^n \beta_4 \Delta \ln REC * GROWTH_{n,t-i} + \sum_{i=1}^n \beta_5 \Delta \ln REC * GROWTH^2_{n,t-i} + \psi ECT_{n,t-1} + \phi_1 \ln CO2_{n,t-1} + \phi_2 \ln REC_{n,t-1} + \phi_3 GROWTH_{n,t-1} + \phi_4 \ln REC * GROWTH_{n,t-1} + \phi_5 \ln REC * GROWTH^2_{n,t-1} + \varepsilon_{n,t} \quad (7)$$

Correction Term (ECT) measures the speed at which the model returns to equilibrium after a disturbance. The expectation is for ψ < 0 (negative and significant) to confirm long-run equilibrium adjustment, indicating that any deviation from equilibrium will gradually correct over time. A negative and statistically significant ECT coefficient further validates the presence of a long-run equilibrium relationship among the variables.

2.3.2. Preliminary Tests

Before estimating the ARDL model, it is crucial to conduct preliminary tests to ensure the reliability and validity of

the results. These pre-tests include the stationarity test, lag optimum test, and cointegration test. The stationarity test, commonly performed using the Augmented Dickey-Fuller (ADF) test, assesses whether the time series data contain a unit root, which would indicate non-stationarity. The null hypothesis assumes the presence of a unit root, and rejection occurs when the ADF test statistic is more negative than the critical value at a given significance level (1%, 5%, or 10%) [58]. The lag optimum test determines the appropriate number of lags to be used in the model estimation, as selecting an optimal lag length at an early stage is essential for obtaining accurate and robust results. This study employs the VAR lag length

Table 2. Descriptive statistics.

Variable	Mean	Median	Min.	Max.	Std. Dev.	Kurtosis
CO2 (Tonnes)	215,259,306	192,483,065	30,781,264	728,883,260	160,826,105	1.9774
NREC (Kilojoule)	3,702,485	3,387,918	1,082,619	9,773,696	1,855,615	3.1537
REC (Kilojoule)	100,475	69,023	4,647	741,218	129,958	11.0401
GROWTH (Percent)	4.476	5.010	-9.518	14.519	3.199	7.5422

Table 3. ADF Stationarity test results.

Variable	Level		Conclusion	1 st Difference		Conclusion
	Stat.	Prob.		Stat.	Prob.	
lnCO2	11.917	0.290	Non-Stationary	46.377***	0.000	Stationary
lnNREC	10.652	0.385	Non-Stationary	31.470***	0.001	Stationary
lnREC	8.795	0.551	Non-Stationary	24.380***	0.007	Stationary
GROWTH	33.419***	0.000	Stationary	66.747***	0.000	Stationary
lnNREC*GROWTH	34.658***	0.000	Stationary	66.965***	0.000	Stationary
lnREC*GROWTH	39.750***	0.000	Stationary	68.113***	0.000	Stationary
lnNREC*GROWTH ²	38.182***	0.000	Stationary	79.169***	0.000	Stationary
lnREC*GROWTH ²	34.854***	0.000	Stationary	79.067***	0.000	Stationary

Note: *** indicates significance at the 1% confidence level.

criteria, particularly the Akaike Information Criterion (AIC), to identify the optimal lag based on the highest number of stars in the output [59]. Lastly, the Johansen panel cointegration test is used to examine whether a stable long-run equilibrium relationship exists among the variables, even if individual variables are non-stationary. This test identifies cointegrating vectors, with statistical significance determined by comparing the test statistic to a critical value [60]. The presence of cointegration confirms that the variables share a long-run relationship, allowing for further analysis using the ARDL model.

3. Results and Discussion

3.1. Descriptive Statistics

Table 2 shows the minimum CO₂ level in 2007 amounted to 30,781,264 in Singapore, and the maximum in 2020 amounted to 728,883,260 in Indonesia. This happens because every year, CO₂ tends to increase. The mean of CO₂ is 215,259,306. The standard deviation is 160,826,105, which means that the tendency of carbon emission data each year during the research time series has a deviation rate of 1.9774. Furthermore, in the NREC variable, the minimum in 2001 was 1,082,619 in the Philippines, and the maximum in 2022 was 9,773,696 in Indonesia. The mean of NREC is 3,702,485. The standard deviation is 1,855,615, which means that the tendency of NREC data each year during the research time series has a deviation rate of 3.1537. In the REC variable, the minimum was 4,647 in 2002 in Malaysia, and the maximum was 741,218 in 2022 in Indonesia. ASEAN-5 annually experiences an increase in the use of REC. The mean of REC is 100,475. The standard deviation is 129,958, which means that the trend of REC data each year during the research time series has a deviation rate of 11.0401. in the GROWTH variable, the lowest in 2020

amounted to -9.518 during the COVID-19 pandemic in the Philippines, and the maximum in 2010 amounted to 14.519 in Singapore. The mean of GROWTH is 4.476. The standard deviation is 3.199, which means that the tendency of GROWTH data each year during the research time series has a deviation rate of 7.5422.

3.2. Stationarity Test

The Augmented Dickey-Fuller (ADF) test is a statistical tool used to determine whether a time series possesses a unit root, thereby indicating its stationarity. The rejection of the null hypothesis, which posits the absence of a unit root, is indicated when the ADF test statistic is smaller (more negative) than the critical value corresponding to the designated significance level. It is imperative to note that the critical value attains its significance due to the number of observations and the selected significance level. For instance, when employing a significance level of 1%, 5% and 10% [58]. The test result is evidenced by the data presented in Table 3; all variables at the first difference level have a p-value that is less than the critical value α . Therefore, it can be concluded that the variables CO₂, NREC, REC, and GROWTH are stationary at the first difference level under various conditions.

3.3. Lag Optimum Test

Lag optimum can be defined as a method for determining the optimal amount of lag to be utilized in the subsequent step. In order to obtain more optimal results, it is of great importance to determine the optimum number of lags at an early stage, prior to the estimation process. In this study, the optimal number of lags will be determined based on the results of the VAR lag length criteria. The optimal lag will be determined based on the largest number of stars and the information criteria

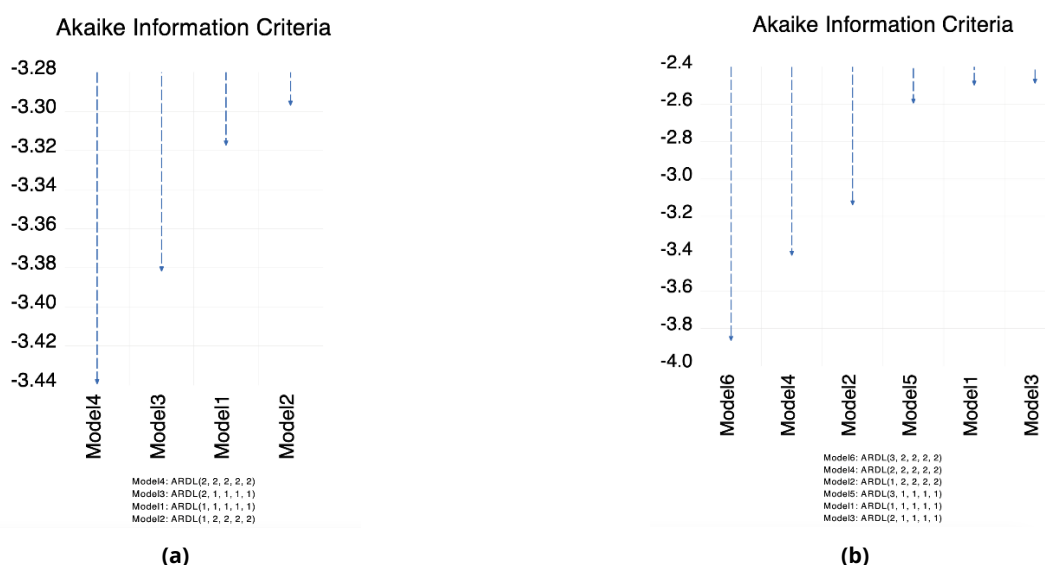


Figure 2. Lag optimum for the NREC (a) and REC (b) models.

Table 4. Cointegration test results.

Null Hypothesis	Fisher Stat.* (from trace test)	Prob.	Conclusion
None	435.30	1.0000	No cointegration
At most 1	61.47***	0.0000	Cointegrated
At most 2	249.70***	0.0000	Cointegrated
At most 3	267.60***	0.0000	Cointegrated
At most 4	245.70***	0.0002	Cointegrated

Note: *** indicates significance at the 1% confidence level.

employed. The information criteria employed are the Akaike Information Criterion (AIC) criteria. The lag optimum of the result is evidenced by the lag length criteria output in the following Figures 2a and 2b; the optimal lag length is determined to be lag 4.

3.4. Cointegration Test

Table 4 presents the findings of the cointegration tests conducted by Johansen. The probability value of the trace statistic or maximum eigenvalue statistic for the Johansen test is below the 5% or 0.05 significance level, indicating that the null hypothesis is rejected and that a cointegration relationship exists. The Johansen cointegration tests collectively demonstrate that this study is cointegrated or exhibits a long-term relationship between the carbon emission variable and the independent variables in the model.

3.5. ARDL Estimation Results

The findings of the study, based on Model NREC presented in Table 5, revealed several significant results. NREC was found to have a statistically significant and positive impact on CO₂ in both the short and long term. A 1% increase in NREC is associated with a 1.4598% increase in CO₂ in the short term, while a 1% increase in NREC leads to a 0.7617% increase in CO₂ in the long term. In the long term, economic growth has a significant and negative impact on CO₂ emissions. A 1% increase in

GROWTH is associated with a 1.2090% decrease in CO₂ in the long term. The interaction between GROWTH and NREC has no effect on carbon emissions in the short term; however, it has a significant and positive effect on CO₂ in ASEAN-5 in the long term. A 1% increase in GROWTH*NREC is associated with a 0.0781% increase in CO₂ in the long term. Similarly, the interaction between squared GROWTH and NREC has no effect on CO₂ in the short term; however, it has a significant and positive effect on carbon emissions in ASEAN-5 in the long term. A 1% increase in NREC*GROWTH and NREC*GROWTH² is associated with a 0.0781% and 0.0002% increase in CO₂ in the long term, respectively.

The objective of Model REC is to estimate and analyze the effect of REC on CO₂, taking into account the moderation effect of economic growth in the ASEAN-5 region. The short-term and long-term results of the Model REC estimation are presented in Table 6. The findings revealed that CO₂ from two periods prior exerts a significant and negative influence on carbon emissions in the short term. REC has no discernible impact on CO₂ in the short term. However, in the long term, REC has a significant and positive effect on CO₂. A 1% increase in REC is associated with a 0.6580% increase in CO₂ in the long term. Similarly, a 1% increase in GROWTH is associated with a 0.4167% increase in CO₂ in the long term. In the short term, the moderation effect between GROWTH and REC has no discernible impact on CO₂.

Table 5. Short-term and long-term results for the NREC model.

Variable	Coeff.	Std. Err.	t-Stat.	Prob.
<i>Short-term</i>				
$\Delta \ln \text{CO}_2(-1)$	-0.0586	0.1847	-0.3174	0.7522
$\Delta \ln \text{NREC}$	1.4598	0.7891	1.8499	0.0701*
$\Delta \ln \text{NREC}(-1)$	-0.7667	1.1797	-0.6499	0.5187
ΔGROWTH	-0.8706	1.0216	-0.8522	0.3981
$\Delta \text{GROWTH}(-1)$	0.2401	0.3886	0.6179	0.5394
$\Delta \ln \text{NREC} * \text{GROWTH}$	0.0566	0.0676	0.8372	0.4064
$\Delta \ln \text{NREC} * \text{GROWTH}(-1)$	-0.0153	0.0247	-0.6180	0.5393
$\Delta \ln \text{NREC} * \text{GROWTH}^2$	-0.0001	0.0001	0.6947	0.4904
$\Delta \ln \text{NREC} * \text{GROWTH}^2(-1)$	-0.0001	0.0001	-0.7732	0.4430
C	2.8073	1.4429	1.9456	0.0572*
ECT(-1)	-0.3845	0.1937	-1.9846	0.0526*
<i>Long-term</i>				
$\ln \text{NREC}$	0.7617	0.1322	5.7682	0.0000***
GROWTH	-1.2090	0.4711	-2.5663	0.0133**
$\ln \text{NREC} * \text{GROWTH}$	0.0781	0.0309	2.5255	0.0147**
$\ln \text{NREC} * \text{GROWTH}^2$	0.0002	0.0001	1.7864	0.0800*

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively.

Table 6. Short-term and long-term results for the REC model.

Variable	Coeff.	Std. Err.	t-Stat.	Prob.
<i>Short-term</i>				
$\Delta \ln \text{CO}_2(-1)$	-0.0544	0.2506	-0.2169	0.8293
$\Delta \ln \text{CO}_2(-2)$	-0.3244	0.1461	-2.2204	0.0320***
$\Delta \ln \text{REC}$	0.5403	0.5339	1.0121	0.3174
$\Delta \ln \text{REC}(-1)$	0.0443	0.7088	0.0625	0.9505
ΔGROWTH	0.3228	0.4856	0.6648	0.5099
$\Delta \text{GROWTH}(-1)$	-0.9600	1.0860	-0.8840	0.3819
$\Delta \ln \text{REC} * \text{GROWTH}$	-0.0258	0.0411	-0.6281	0.5335
$\Delta \ln \text{REC} * \text{GROWTH}(-1)$	0.0679	0.0799	0.8499	0.4003
$\Delta \ln \text{REC} * \text{GROWTH}^2$	0.0001	0.0001	0.5513	0.5844
$\Delta \ln \text{REC} * \text{GROWTH}^2(-1)$	0.0017	0.0014	1.0913	0.2815
C	3.5798	1.6898	2.1184	0.0402**
ECT(-1)	-0.2907	0.1284	-2.2639	0.0289**
<i>Long-term</i>				
$\ln \text{REC}$	0.6580	0.0435	15.1694	0.0000***
GROWTH	0.4167	0.2506	10.7433	0.0000***
$\ln \text{REC} * \text{GROWTH}$	-0.0369	0.0037	-10.0912	0.0000***
$\ln \text{REC} * \text{GROWTH}^2$	-0.0006	0.0001	-8.5840	0.0000***

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% confidence levels, respectively.

However, in the long term, this moderation has a clear, significant, and negative effect on CO₂ within the ASEAN-5 region. A 1% increase in REC*GROWTH and REC*GROWTH² is associated with a 0.0369% and 0.0006% decrease in CO₂ in the long term, respectively.

Figure 3 presents the results of both the NREC and REC models, providing a clear visual representation of the long-term impact of each variable for easier interpretation.

3.6. Heteroscedasticity Test

The results of the heteroscedasticity test are illustrated in Figure 4a-b. The model in this study is free from heteroscedasticity issues. This conclusion is derived from the residual graph (blue color), which does not cross the boundary (500 and -500), indicating that the residual

variance is consistent. Thus, there are no indications of heteroscedasticity, and the model can be considered to exhibit homoscedasticity or to be free of heteroscedasticity.

3.7. Discussion

The outcomes of the NREC and REC models are manifestly distinct. In the REC model, there is no immediate correlation between renewable energy consumption and CO₂. Nevertheless, the NREC model has demonstrated that the consumption of non-renewable energy has a direct and positive effect on carbon emissions in the short term. The results demonstrate that economic growth exerts an influence that accelerates the consumption of both non-renewable and renewable energy over the long term. The findings of this research

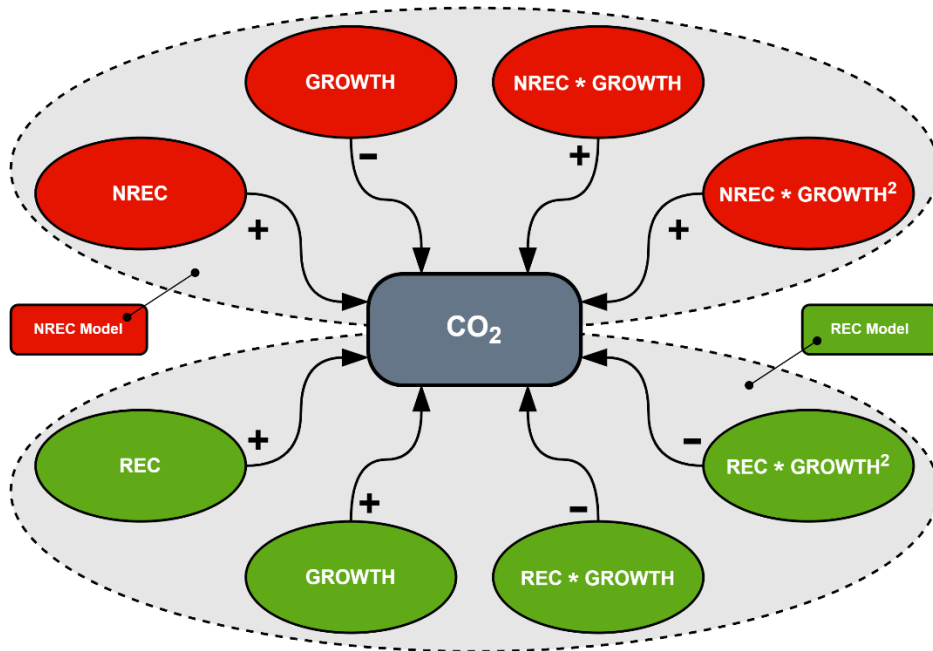
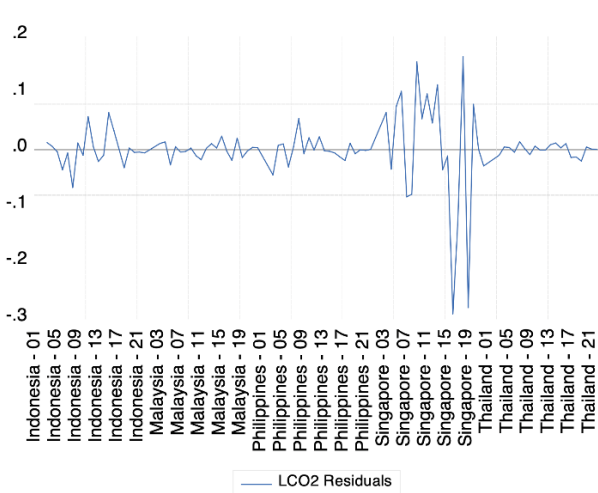
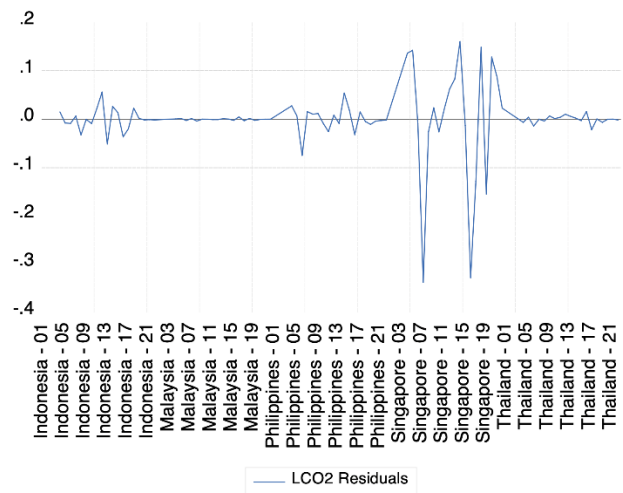


Figure 3. The graphical results of the long-term impact of the NREC model and REC model.



(a)



(b)

Figure 4. Residual graph for NREC (a) and REC (b) models.

indicate that the EKC model, which posits that economic expansion driven by excessive non-renewable energy consumption can stimulate long-term growth in the ASEAN-5 region, also has a positive impact on carbon emissions. In light of these findings, it can be posited that economic growth in the ASEAN-5 is still in its nascent stages with regard to the EKC theory. The EKC economic growth model, which is influenced by renewable energy consumption, has been found to contribute negatively to carbon emissions when compared to growth influenced by non-renewable energy consumption.

These findings demonstrate that the consumption of non-renewable energy sources, including petroleum, coal, and others, has a detrimental impact on the

environment, particularly through carbon emissions. This result aligns with the findings of Wang et al. [41], Idroes et al. [43], and Kartal et al. [44], which indicate that the use of non-renewable energy sources contributes to environmental degradation. Similarly, González-Álvarez [61] has identified a correlation between CO₂ emissions and energy consumption, whereby economic activity exerts an increasingly pronounced influence on this relationship. The findings of this study highlight the necessity of governmental policies to regulate fossil fuel consumption and mitigate its adverse environmental effects [31, 62].

The extraction of fossil fuel energy resources necessitates regulations that set time limits on their

extraction to mitigate environmental damage. Such regulations have a positive impact on reducing environmental harm, as highlighted by research from Piggot [63], Dam et al. [64], and Xia et al. [65]. Our study's findings emphasize that restricting fossil fuel extraction is a crucial policy transition for mitigating environmental degradation. Policies may include measures such as restricting energy consumption, implementing emission taxes, and promoting environmental education and awareness. For instance, incorporating environmental topics into school curricula can foster a sense of responsibility and awareness among young children. At the community level, village leaders can encourage energy efficiency and support eco-friendly practices. On a broader scale, governments can introduce regulations targeting industrial activities to reduce carbon emissions and promote sustainable practices. Collectively, these efforts can create a more environmentally conscious society and help safeguard the planet for future generations. Another potential policy option is to limit energy consumption or implement emission taxes.

Furthermore, this study finds that increased renewable energy consumption leads to elevated CO₂ emissions. While this finding contrasts with the general literature, theories such as the Green Solow Model (GSM) by Brock & Taylor [66] argue that every input in production contributes to increased emissions, potentially leading to environmental consequences. These findings are supported by researchers such as Bilgili et al. [67], Shahzad et al. [68], and Fu et al. [69], who found similar results indicating that renewable energy consumption has a positive impact on CO₂ emissions. This suggests that, over time, higher energy consumption in ASEAN-5 countries will result in increased CO₂ emissions, exacerbating environmental pollution. It is crucial for governments in the region to play a more active role in transforming energy consumption patterns [70]. The transition from non-renewable to renewable energy sources is insufficient if not accompanied by comprehensive and well-planned strategies, as poorly executed transitions may lead to unintended environmental consequences [39]. Infrastructure development and downstream resources related to energy transformation must be conducted in an environmentally responsible manner.

In the long run, the NREC and REC models show opposite effects on CO₂ emissions. In the NREC model, economic growth is found to reduce CO₂ emissions over time, possibly due to improved energy efficiency, technological advancements, or a gradual shift toward cleaner energy sources. However, the REC model shows a positive impact on CO₂ emissions, suggesting that renewable

energy use in ASEAN-5 is not yet sufficient to lower emissions. This could be due to reliance on fossil fuel backups, emissions from renewable infrastructure, or inefficiencies in the energy transition. Additionally, economic growth in ASEAN-5 has a significant and positive impact on carbon emissions, contradicting the EKC theory, which suggests emissions should decline after reaching a certain economic level. Instead, evidence shows that rising economic activity continues to drive emissions in the region [38, 71-73].

In the moderating model, non-renewable energy consumption has a positive impact on CO₂ emissions, with economic growth intensifying this relationship. Additionally, the interaction between economic growth squared and non-renewable energy consumption also shows a positive impact. As economies expand, industrial activity, energy demand, and fossil fuel consumption rise, exacerbating environmental degradation. While economic growth can provide resources for cleaner technologies, without a strategic shift toward renewable energy, it risks reinforcing carbon-intensive development. Therefore, policymakers must implement sustainable energy strategies to ensure that economic progress does not come at the cost of environmental harm.

Regarding renewable energy, this study's findings indicate that in the short term, economic growth through renewable energy consumption does not significantly reduce carbon emissions. However, in the long run, this relationship becomes significant, as Mahmood et al. [74] found that per capita income inflows influence renewable energy in a way that cancels out its benefits for reducing CO₂ emissions, leading to negative environmental effects. The interaction between economic growth squared and renewable energy consumption has no short-term effect on emissions but exerts a negative and significant influence in the long term. This aligns with the EKC theory, which suggests that after reaching a peak in economic growth, societies recognize the environmental impact of their actions and shift toward sustainable energy solutions. As renewable energy adoption increases, emissions decline, mitigating environmental damage [10, 13, 75, 76]. Ultimately, this study suggests that long-term economic growth, when coupled with renewable energy expansion, can contribute to reducing carbon emissions in ASEAN-5.

4. Conclusions and Policy Recommendations

The consumption of non-renewable and renewable energy has a positive and significant impact on carbon emissions in the long term. In contrast, the consumption of non-renewable energy has a positive and significant

impact on carbon emissions in the short term. This is due to the weak enforcement of environmental regulations and the abuse of power, exploitation of natural resources, evasion of environmental sanctions, and embezzlement of budgets for environmental protection, which collectively exacerbate the ecological degradation of the ASEAN-5. The moderation between economic growth and the consumption of non-renewable and renewable energies has no effect on carbon emissions in the short term. However, in the long term, the moderation between economic growth and non-renewable energy consumption has a positive and significant effect on carbon emissions, while the moderation between economic growth and renewable energy consumption has a negative and significant effect on carbon emissions in the ASEAN-5.

The moderation between economic growth squared with non-renewable energy consumption and renewable energy consumption has no effect on carbon emissions in the short term. Nevertheless, in the long term, there is a positive and significant correlation between non-renewable energy consumption and carbon emissions, while renewable energy consumption has a negative and significant effect on carbon emissions in the ASEAN-5. The economic growth driven by non-renewable energy consumption impacts environmental damage through carbon emissions. An enhanced educational system contributes to the incremental diminution of environmental degradation as environmental consciousness expands within society and the industrial sector.

Researchers propose the implementation of green development policies, such as the use of renewable energy and natural resource efficiency, as a means of encouraging sustainable economic growth and mitigating environmental damage in the long term. It is imperative to address the adverse effects on the environment by reinforcing law enforcement and environmental regulations, as well as enhancing transparency in the licensing process and natural resource management to curtail corrupt practices that impair the ecosystem. Furthermore, it is crucial to instill environmental awareness from an early age. The government must prioritize environmental education at the community and corporate levels. Additionally, the government must set a policy regarding the time limit for the extraction of non-renewable energy resources. This would allow the environment to recover from the damage caused by the resource extraction process. Regulations on the time limit for resource extraction are one solution, as the current practice is to extract non-renewable natural resources until they are exhausted. This practice often

results in environmental degradation as the site is subsequently abandoned without any effort to restore the environment.

The generalizability of the study's findings is limited, as it is specifically focused on ASEAN-5, and therefore, its findings might not be fully applicable to other regions with different energy policies, industrial structures, or urbanization patterns. Additionally, the study does not fully capture time lag effects, meaning that long-term shifts in technology, energy transitions, and policy changes may alter the observed relationships over time. The implementation and enforcement of policies differ across ASEAN-5 countries, introducing further complexity due to the potential for economic growth to moderate emissions in different ways depending on the effectiveness of national policies. Finally, the study focuses on aggregate energy consumption and emissions without a detailed sectoral breakdown. To enhance the accuracy and policy relevance of future research, it is recommended that sector-specific analysis, long-term data, and advanced econometric methods be incorporated.

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