THE INFLUENCE OF ECONOMIC GROWTH, POPULATION, ENERGY CONSUMPTION, AND HDI ON CARBON DIOXIDE (CO_2) GAS EMISSIONS IN ASEAN COUNTRIES

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ABSTACT

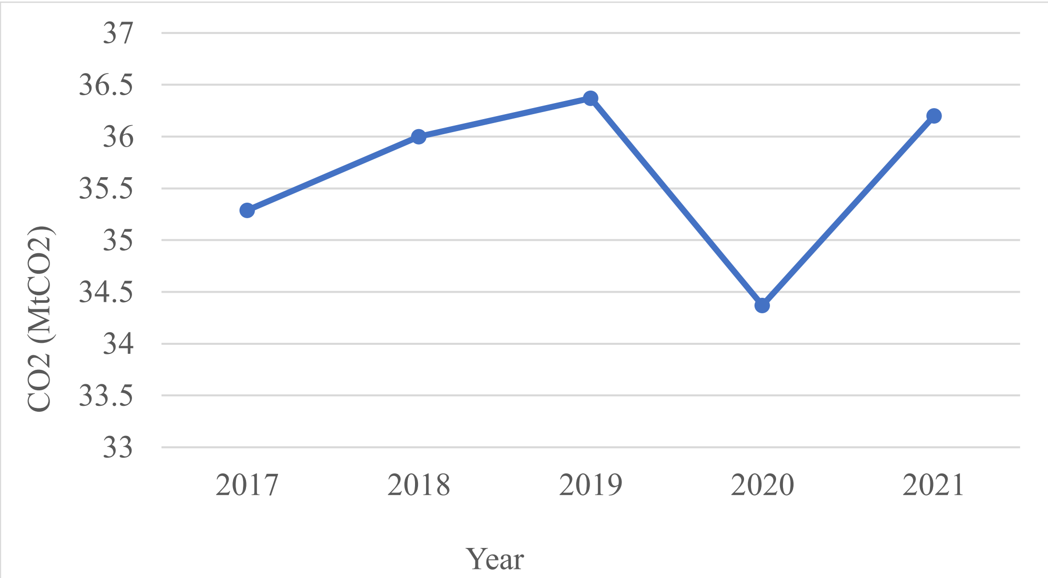
This research aims to analyze the impact of economic growth, population, energy consumption, and Human Development Index (HDI) on Carbon Dioxide (CO_2) emissions in 11 ASEAN countries during the period 2013–2021. The research applies a dynamic panel regression method using the Generalized Method of Moments (GMM) approach. The research results indicate that although Economic Growth (GDP) has a positive yet insignificant impact in the short term, it shows a weak and positive impact in the long term, indicating continued reliance on fossil energy that has not been separated completely from economic growth. Population (POP) has a positive and significant impact on CO_2 emissions, both in the short and long term, indicating that increasing population leads to higher energy demand and greater economic activity. Energy Consumption (ERG) has an insignificant impact, due to the diversity of energy sources, including renewable energy, or measurement inefficiencies. The Human Development Index (HDI) has a negative and significant impact, especially in the long term, showing that improving human quality through education, health, and the economy can promote sustainable development and reduce CO_2 emissions. The policy implications of this research include controlling the impact of population through sustainable urban planning, strengthening environmentally based Human Development, decarbonizing economic growth, and implementing long-term strategies such as regional collaboration for a clean energy transition. These findings contribute theoretically to the advancement of the Environmental Kuznets Curve (EKC) model.

Keywords: CO_2 Emissions, Economic Growth, Population, Energy Consumption, HDI, ASEAN, Dynamic Panel Regression

INTRODUCTION

Sustainable development has been the main agenda of countries in the world since the 1980s. This development concept emphasizes meeting the needs of the present generation without compromising the ability of future generations to meet their own needs (Zaman & Moemen, 2017). The Sustainable Development Goals (SDG's) agenda adopted at the UN Conference in Rio de Janeiro in 2012 contains 17 main goals, one of which is climate change control (Olubiyi, 2020). Climate change is currently an existential threat to humanity, characterized by an increase in earth's temperature, intensification of hydro-meteorological disasters, and various other socio-economic impacts (Putra & Rusgianto, 2023). Recent reports show that global temperatures have increased by 1.1°C since the pre-industrial era, and atmospheric carbon concentrations have reached 419 ppm, exceeding the safe limit of 350 ppm (INFORSE-Europe, NASA). Global efforts to reduce carbon emissions, such as the 2015 Paris Agreement and the Carbon Disclosure Project (CDP) initiative, emphasize the importance of collaboration across countries and sectors to achieve the targets of 45% emission reduction by 2030 and carbon neutral by 2050.

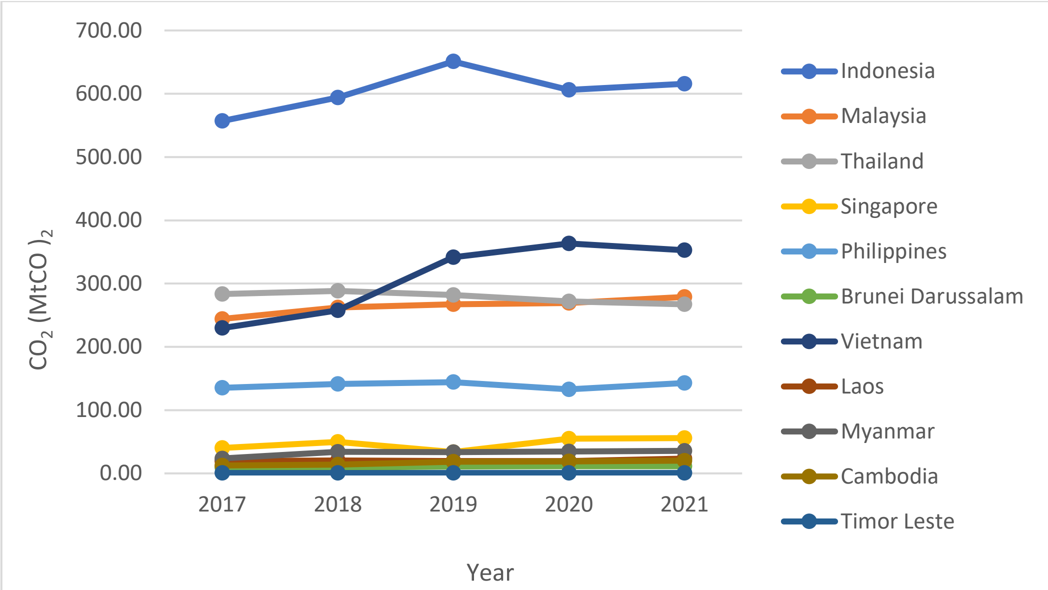
(Tanjung et al., 2025)While much of the literature focuses on the dynamics of carbon emissions in developed countries, the phenomenon of rising emissions in developing countries is receiving increasing attention. Developing countries in Asia, particularly the ASEAN region, now account for nearly half of total global emissions, up significantly from two-fifths in 2015 (Balsamo et al., 2023).



Source: Statista (2024)

Figure 1.
World Carbon Emissions Data 2017-2021

The data shows that the trend of CO_2 emissions in ASEAN continues to increase without any indication of a significant decline, especially after the economic recovery after the Covid-19 pandemic.



Source: Global Carbon Project (2024)

Figure 2.
ASEAN CO_2 Emissions 2017-2021

Indonesia, Vietnam, Malaysia, and Thailand are the largest contributors to carbon emissions in Southeast Asia, driven by massive economic growth, urbanization, and population increase. This is exacerbated by the "grow first, clean up later" approach adopted by many ASEAN countries, where economic development is often at the expense of the environment (Liu et al., 2023). This strategy has proven to have high social and ecological costs, and has the potential to threaten the long-term sustainability of growth.

(Andrasari et al., 2024)The issue of carbon emissions in the ASEAN region cannot be separated from the complex interactions between economic growth (GDP), population dynamics, energy consumption, and the quality of human development (HDI). The Environmental Kuznets Curve (EKC) theory suggests an inverted U-shaped causality between carbon emissions and economic growth (Zhang et al., 2023). In the early phase of development, an increase in GDP tends to drive carbon emissions, but after passing the turning point, technological innovation and a shift to a service-based economy can reduce emissions(Anser et al., 2021). However, empirical evidence in the ASEAN region is mixed and often does not consistently support the EKC hypothesis (Zhao et al., 2021). Population and energy consumption variables are also important determinants in the IPAT model (Impact = Population × Affluence × Technology), where population growth and fossil energy consumption directly increase environmental pressure.

There is a significant research gap in previous studies regarding the integration of analysis between economic, population, energy and HDI variables on CO_2 emissions in ASEAN(Shafique et al., 2023). Many previous studies only tested two or three variables separately, or were limited to one country or group of countries with a certain income level (Dumor et al., 2022). Some studies show that GDP and energy consumption have a significant positive effect on emissions, while population and HDI often produce inconsistent findings depending on the model, period and country sampled (Osei-Kusi et al., 2024). In addition, studies with dynamic panel regression (GMM) approaches that are able to distinguish short-run, long-run, and convergence effects among countries in the ASEAN region are still very limited(Malik & Sharma, 2025). In fact, the complexity of linkages between economic and environmental indicators in ASEAN demands more robust longitudinal and comparative analysis(Ghanem & Alamri, 2023).

This study offers novelty by integrating all key indicators-GDP, population, energy consumption, and HDI-into one Generalized Method of Moments (GMM)-based dynamic panel model, and testing both short-run, long-run, and convergence effects. In addition, the data coverage of 11 ASEAN countries over the period 2013-2021 provides a more comprehensive understanding, beyond the limitations of previous cross-country or single-country studies(Sun et al., 2020). Thus, the results of this study can serve as an evidence-based policy reference in the formulation of energy transition strategies, sustainable development, and efforts to achieve the SDGs at the regional level. This research also enriches the development of the EKC and IPAT models by adding a human development perspective that was previously less empirically explored in the ASEAN region.

RESEARCH METHOD

This study uses a quantitative approach with a dynamic panel design to analyze the effect of economic growth (GDP), population, energy consumption, and Human Development Index (HDI) on carbon dioxide (CO_2) gas emissions in ASEAN countries during the period 2013-2021. The study population consists of 11 ASEAN member countries, namely Indonesia, Malaysia, Singapore, Cambodia, Vietnam, Laos, Thailand, Philippines, Myanmar, Brunei Darussalam, and Timor Leste. The sampling technique uses *census sampling* because all ASEAN countries that have complete data during the observation period are included as units of analysis. The data used is secondary panel data (a combination of time series and cross section data) taken from official sources, namely the World Bank, Global Carbon Project, United Nations Development Program (UNDP), and ASEAN Center of Energy.

Table 1.
Variables, Symbols, Units, and Data Sources

Variable	Symbol	Unit	Source
Carbon Emission	CO_2	$MtCO_2$	Global Carbon Project
Economic Growth	GDP	%	World Bank
Population	POP	Million People	ASEAN Center of Energy
Energy Consumption	ERG	% of total access population	World Bank
Human Development Index	HDI	0-1 points	United Nations Development Programme (UNDP)

The variables analyzed include carbon emissions (CO_2, $MtCO_2$), economic growth (GDP, %), population (million), energy consumption (percentage of energy access from total population), and HDI (index 0-1). The operational definitions of the variables are detailed in the data collection process is done digitally by accessing the database of each official institution, so that the validity of the data is guaranteed and can be verified by other researchers.

Table 2.
Operational Definition of Variables

Variable	Symbol	Operational Definition	Unit	Data Source
Carbon Emission	CO_2	Is the release of carbon dioxide (CO_2) into the atmosphere that occurs naturally or is triggered by human activities such as deforestation, electricity use, and industrial manufacturing activities.	$MtCO_2$	Global Carbon Project
Economic Growth	GDP	Total income in a country as measured by GDP growth in one period.	%	World Bank
Population	POP	Total population growth in a country over time.	Million Souls	ACE
Energy Consumption	ERG	The amount of energy access by households, industry, transportation, and other sectors based on total access from the population.	%	World Bank
Human Development Index	HDI	HDI describes a country's average achievement in the basic aspects of human development namely, health, education, and economy.	Scale points 0-1	UNDP

(Pasaribu et al., 2023)Data analysis was conducted using the dynamic panel regression method using the Generalized Method of Moments (GMM) approach, which consists of two main models: First-Difference GMM (FD-GMM) and System GMM (SYS-GMM) according to the Arellano-Bond and Blundell-Bond frameworks. These models were chosen to overcome potential endogeneity, heterogeneity, and simultaneous bias among variables, as well as to estimate short-run, long-run effects, and the speed of convergence to equilibrium (steady state). The analysis process includes the following stages: correlation matrix analysis, FD-GMM and SYS-GMM model estimation, parameter specification test (Sargan test, Arellano-Bond test), selection of the best model based on instrument validity and estimator unbiasedness (comparison with Fixed Effect Model and Pooled Least Squares), and simultaneous (Wald test) and partial (Z test) model significance testing. All analyses were conducted using R Studio and EViews software, following the latest panel data statistical rules.
Mathematically, the dynamic panel regression model used is formulated as follows:

$$CO_{2_{i,t}} = \beta_0 + \delta CO_{2_{i,t-1}} + \beta_1 GDP_{i,t} + \beta_2 POP_{i,t} + \beta_3 ERG_{i,t} + \beta_4 IPM_{i,t} + \varepsilon_{i,t}$$

Where,

$CO_{2_{i,t}}$: Carbon Emissions in period t
β_0 : Constant value
δ : Explanatory endogenous variable coefficient
$GDP_{i,t}$: Economic Growth in period t
$POP_{i,t}$: Population in period t
$ERG_{i,t}$: Energy Consumption in period t
$IPM_{i,t}$: Human Development Index in period t
β_{1-4} : Coefficient vector of predictor variable
$\varepsilon_{i,t}$: Panel regression error of the i-th observation unit in the t-th period

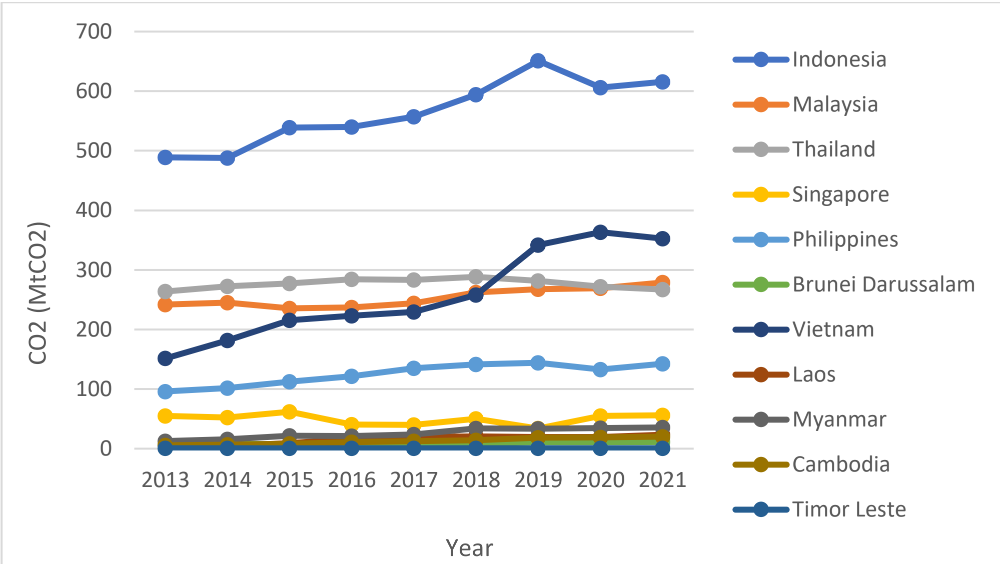
Model specification tests include testing residual autocorrelation (Arellano-Bond), instrument validity (Sargan test), and unbiasedness of dependent lag estimates. For the interpretation of long-run elasticity, the formula LRE $=\frac{\beta}{1-\alpha}$ is used, allowing for convergence analysis and robust estimation of long-run effects.

RESULTS AND DISCUSSION

This study analyzes 11 ASEAN countries (Indonesia, Malaysia, Thailand, Singapore, Philippines, Brunei Darussalam, Vietnam, Laos, Myanmar, Cambodia, Timor Leste) in the period 2013-2021. Variables observed: Carbon Emissions (CO_2), Economic Growth (GDP), Population (POP), Energy Consumption (ERG), and Human Development Index (HDI).

Carbon Emissions in ASEAN

ASEAN contributes 4-5% of global carbon emissions. Indonesia is the largest contributor (40% of total ASEAN emissions), driven by its coal-based energy sector and deforestation.



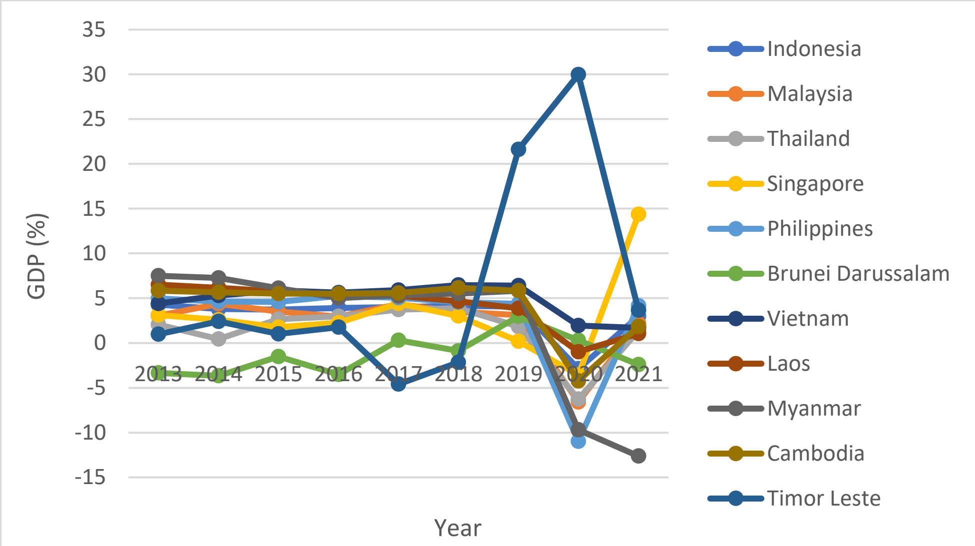
Source: Global Carbon Project

Figure 3.
ASEAN Carbon Gas (CO_2) Emissions 2013-2021

The graph shows that Indonesia is the highest CO2 emitter in ASEAN with a significant upward trend, influenced by deforestation, peatland fires, and reliance on coal as an energy source. Despite mitigation efforts such as a moratorium on forest licenses, renewable energy development, and a net zero emission target for 2060, structural challenges such as corruption and economic pressures hinder their effectiveness. Meanwhile, Vietnam has experienced the fastest spike in emissions due to industrialization, and smaller countries such as Singapore, Brunei, and some developing countries in the region show a pattern of low emissions but increasing with economic growth. This highlights the importance of a sustainable strategy to balance development with carbon emission reduction in ASEAN.

Economic Growth in ASEAN

ASEAN is the fastest-growing economic region in the world, recording an average GDP growth of 5.2% per year in the last decade, albeit with disparities between countries. Vietnam and the Philippines are driving growth with strong export and FDI performance, while Indonesia, Thailand, and Malaysia are growing steadily through the industrial and commodity sectors. On the other hand, Myanmar, Laos, and Cambodia face structural bottlenecks such as political crises, dependence on agriculture, and weak infrastructure. Rapid economic growth is driving increased energy demand, especially for industry, transportation, and infrastructure. However, challenges such as export dependency, infrastructure limitations, and global risks such as post-pandemic stagflation and geopolitical conflicts could hamper stability and equitable growth in the region.



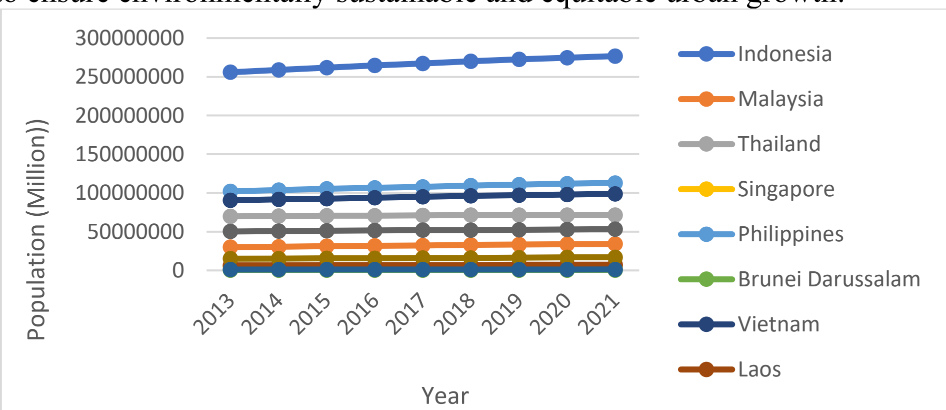
Source: World Bank

Figure 4.
ASEAN Economic Growth (GDP) 2013-2021

From the graph above, there are fluctuations in GDP due to the pandemic, but the trend is positive before 2020. This is due to export dependence, uneven infrastructure, risk of post-pandemic stagflation.

Population in ASEAN

ASEAN, with a population of around 670 million by 2023, faces complex demographic and urbanization challenges. Countries such as Indonesia, the Philippines and Vietnam have a demographic bonus with a majority of young people, while Thailand and Singapore face an aging population and the risk of a labor crisis due to low fertility rates. Rapid urbanization, especially in major cities such as Jakarta, Manila, and Bangkok, is causing problems such as overcrowding, air pollution, and pressure on infrastructure and basic services. With growing urbanization-projected to reach 66% of ASEAN's population by 2050-the region will experience a surge in energy demand, especially in cities characterized by high consumption of transportation, buildings, and appliances. This challenge demands sustainable and inclusive planning to ensure environmentally sustainable and equitable urban growth.



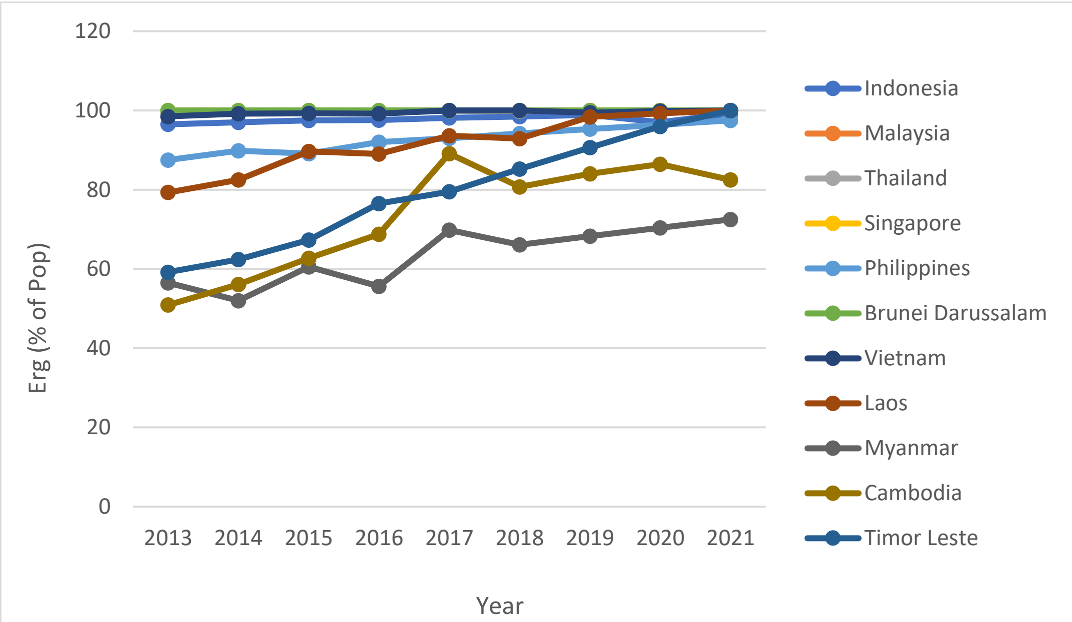
Source: ASEAN Center of Energy

Figure 5.
ASEAN Population 2013-2021

Indonesia has the largest population in ASEAN, reaching 276 million in 2021, and is the fourth most populous country in the world after China, India and the United States. The country's 1.9 million km² land area, tropical climate, and rich natural resources have historically contributed to its population growth. The Philippines and Vietnam also boast large populations of more than 100 million, despite their smaller territories. Meanwhile, Thailand and Vietnam are beginning to experience a decline in birth rates due to successful family planning programs. Countries such as Singapore, Brunei Darussalam and Timor Leste have much smaller populations, reflecting the slowing demographic dynamics in parts of the ASEAN region. These population variations reflect the different development challenges and opportunities among countries in the region.

Energy Consumption in ASEAN

Energy consumption in ASEAN is growing rapidly at 4% per year, exceeding the global average, with 80% of energy supply still dependent on fossil fuels such as coal, oil and natural gas. Indonesia and Vietnam are the largest users of coal, while Singapore relies heavily on energy imports. However, the transition to renewable energy is making progress, with Vietnam leading the way in solar power and Laos developing hydropower for export. Thailand and the Philippines are also innovating in wind and geothermal energy. However, major challenges still hinder the region's clean energy transition, including fuel subsidies in Indonesia and Malaysia, lack of investment in renewable energy integration, and energy import dependency in some countries such as Singapore.



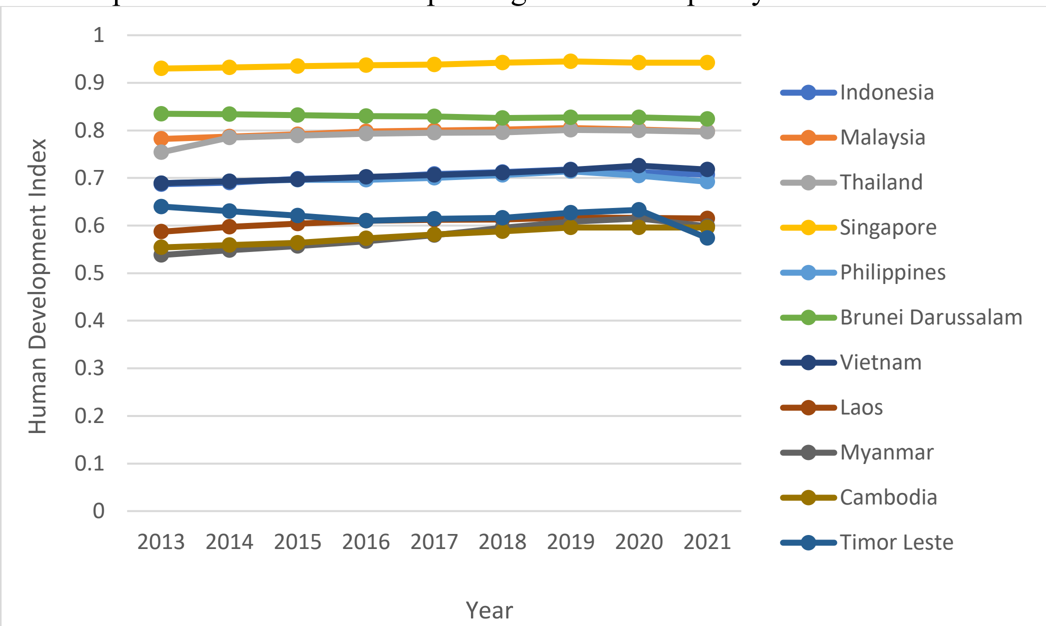
Source: World Bank

Figure 6:
ASEAN Energy Consumption 2013-2021

According to the graph, Singapore, Malaysia and Brunei Darussalam have achieved 100% energy access since 2013, reflecting the high and stable level of energy consumption as the population grows. Indonesia has seen a significant increase in energy consumption due to its large population, industrial development, energy-intensive transportation, and subsidy policies that encourage consumption. Vietnam is also making progress with energy access increasing from 98.5% in 2013 to 100% in 2021. Meanwhile, countries like Myanmar and Cambodia still face energy access challenges, despite improvements. Timor Leste showed great leaps with access increasing from 59.2% to 100% in eight years. However, the transition to clean energy remains a regional priority to reduce dependence on fossil fuels.

Human Development Index (HDI) in ASEAN

The Human Development Index (HDI) is an important indicator that measures the quality of a country's development through three main aspects: health, education, and living standards. Although ASEAN countries have varying levels of Gross National Income per capita, their human development outcomes are not always comparable, reflecting differences in each country's policy effectiveness and priorities. Singapore and Brunei Darussalam are classified in the very high HDI category, showing outstanding achievements in all three dimensions. Malaysia and Thailand fall into the high category, while countries such as Indonesia, Vietnam and the Philippines remain at intermediate HDI levels, along with Cambodia, Laos and Myanmar. This variation confirms that economic growth alone is not enough without policies that focus on improving the overall quality of life.



Source: United Nations Development Program (UNDP)

Figure 7.
ASEAN Human Development Index (HDI) 2013-2021

The graph shows significant differences in the HDI of ASEAN countries, with Singapore in the very high category, Malaysia and Thailand high, and Indonesia, the Philippines and Vietnam in the middle level. Countries such as Myanmar, Cambodia and Laos are still lagging behind due to conflict and limited infrastructure. Despite improving HDI, ecological awareness in the region remains low, characterized by weak environmental education and law enforcement. Inequality in access to public services in rural areas also hinders HDI improvement. To achieve its vision as a global economic power by 2030, ASEAN needs to promote clean energy transition, equitable development, and stronger environmental education.

Statistical Analysis and Correlation Results

Table 3.
Results of Descriptive Statistical Analysis

	CO_2	GDP	POP	ERG	HDI
Mean	144.5895	3.013204	59576934	90.72626	0.713293
Median	52.10940	3.749844	32355644	98.50000	0.702000
Maximum	650.9059	29.97670	2.77E+08	100.0000	0.945000

Minimum	0.589620	-12.62948	411202.0	50.90000	0.538000
Std. Dev.	172.4898	5.269663	75499891	13.91513	0.111533
Skewness	1.296246	1.063410	1.779393	-1.487073	0.437656
Kurtosis	3.863595	11.02775	5.460684	3.922700	2.294974
Jarque-Bera	30.80060	284.4936	77.21966	39.99978	5.210827
Probability	0.000000	0.000000	0.000000	0.000000	0.073873
Sum	14314.36	298.3072	5.90E+09	8981.900	70.61600
Sum Sq.Dev.	2915767.	2721.396	5.59E+17	18975.83	1.219093
Observations	99	99	99	99	99

Source: EViews Data Processing Output Results

Descriptive statistics show high variability for CO_2, GDP, POP; homogeneous for ERG and HDI.

Table 4.
Correlation Analysis Results

	CO_2	**GDP**	**POP**	**ERG**	**HDI**
CO_2	1.000000	-0.030887	0.876426	0.429495	0.192925
GDP	-0.030887	1.000000	0.004982	-0.085436	-0.201160
POP	0.876426	0.004982	1.000000	0.198795	-0.056489
ERG	0.429495	-0.085436	0.198795	1.000000	0.693093
HDI	0.192925	-0.201160	-0.056489	0.693093	1.000000

Source: EViews Data Output Results

Strong correlation between CO_2-POP (0.876), ERG-IPM (0.693), CO_2-ERG (0.43); GDP is not significantly correlated with CO_2 or HDI.

Dynamic Panel Estimation Results (SYS-GMM)

FD-GMM Estimation Results

The Arellano-Bond First Difference GMM (FD-GMM) method should produce unbiased, consistent, and efficient estimates; the results are shown in the table below.

Table 5.
FD GMM Estimation Results

Variable	FD-GMM
-lag(log(co2))	0.2806*
log(pop)	1.176
GDP	-0.0016
ERG	0.0123*
HDI	4.7648***

Source: R Studio Data Processing Results

FD-GMM (Generalized Method of Moments) estimation results using panel data of 11 countries (n), 9 time periods (T), and 99 observations (N). The coefficient of lag(log(co2)) is 0.2806 (significant at 5%). There is a relationship and dependency between CO_2 emission variables from year to year, but it is lower than the models (System-GMM two-step 0.9726, and Fixed Effect 0.6135). The previous year's emissions influenced the current year's emissions by 28.06%, indicating a moderate relationship. FD-GMM is more conservative as it only uses difference equations.

Parameter Significance Test Results on the FD-GMM Model

Parameter significance testing is used to determine the relationship in the model. In the FD-GMM estimation, the Wald test was conducted with a value of chi-sq (5) = 94.40138 (p-value = 0), indicating that the coefficients are jointly highly significant. The FD-GMM model statistically explains the variation in CO_2 emissions.

FD-GMM Model Specification Test Results

The model to be selected must meet consistency, validity, and unbiasedness. So the model specification test was carried out on FD-GMM, and the results can be shown in the following table.

Table 6.
FD-GMM Model Specification Test Results

Model Specifications	P-Value
Sargan test	11 (p-value = 0.99724)
Autocorrelation test (2)	-1.864124 (p-value = 0.062304)

Source: R Studio Data Processing Results

a. Consistency Test Results (Arrelano-Bond Test)

The Arellano Bond test is used to ensure that the error term is not serially correlated in AR(2) so that the estimate obtained is consistent with the null hypothesis that there is no autocorrelation (AR(2)>0.05). It is known that the value of AR(2) is insignificant (0.062304) indicating no second-order autocorrelation, the estimate obtained is consistent with the GMM estimator.

b. Validity Test Results (Sargan Test)

The Sargan test is used to identify the validity of all instrument variables whose number exceeds the number of estimated parameters (over-identifying) with the null hypothesis that the instrument is valid. In addition to testing the validity of the instrument variables, this test is also used to see whether the residual data of the GMM estimation is homoscedasticity. The value of chi-sq(27) = 11, p-value = 0.99724, indicates H0: The instrument is valid (uncorrelated with the error term). Hence, it is concluded that we fail to reject H0 (instrument is valid). A high p-value indicates no evidence of violation of the instrument assumptions.

c. Unbiasedness Test Results

The unbiasedness criterion is obtained from comparing the GMM dependent lag estimator with FEM (Fixed Effect Model) which is biased downward and PLS (Pooled Least Squares) which is biased upward. The unbiased estimator will be between the FEM and PLS models. The dependent lag coefficients are as follows.

Table 7.
Comparison of FD-GMM Dependent Lag Coefficient

Estimation	Coefficient Value
FEM	0.61351964
FD-GMM	0.2806461
PLS	1.00427064

Source: R Studio Data Processing Results

From the comparison of the above results, it can be concluded that the unbiasedness is not met because the FD-GMM dependent lag coefficient is below FEM and PLS. The model specification test criteria are not met, so the model estimation continues with SYS-GMM.

SYS-GMM Estimation Results

BlundellBond's System Generalized Method of Moments (SYS-GMM) estimation method is used to estimate the system of equations by combining the first difference with the level condition. The SYS-GMM estimation results can be shown below.

Table 8.
SYS-GMM Estimation Results

Variable	SYS-GMM
-lag(log(co2))	0.9726***
log(pop)	0.0186***
GDP	0.0022
ERG	0.0002
HDI	-0.2226*

Source: R Studio Data Processing Results

The coefficient of lag(log(co2)) is 0.9726 (significant at 0.1%). There is a high dependence between CO2 emission variables from year to year, values close to 1 indicate that CO_2 emissions are strongly influenced by previous values.

Parameter Significance Test Results on the SYS-GMM Model

Parameter significance testing is used to determine the relationship in the model. In the SYS-GMM estimation, the Wald test was used to test the significance of the model simultaneously to get the results of chi-sq (5) = 482098.2 (p-value = 0), indicating that the coefficients are jointly highly significant. The SYS-GMM model statistically explains the variation in CO_2 emissions.

SYS-GMM Model Specification Test Results

Model specification tests on SYS-GMM include the Arellano-Bond test, the Sargan test and the unbiased test, the results of which are as follows.

Table 9.
SYS-GMM Model Specification Test Results

Model Specifications	P-value
Sargan test	11 (p-value = 0.99999)
Autocorrelation test (2)	-0.7843861 (p-value = 0.43281)

Source: R Studio Data Processing Results

a. Consistency Test Results (Arrelano-Bond Test)

The Arellano Bond test is used to ensure that the error term is not serially correlated in AR(2) so that the estimate obtained is consistent with the null hypothesis that there is no autocorrelation (AR(2)>0.05). It is known that the value of AR(2) is not significant (0.433) indicating that there is no second-order autocorrelation, the estimate obtained is consistent with the GMM estimator.

b. Validity Test Results (Sargan Test)

The Sargan test is used to identify the validity of all instrument variables whose number exceeds the number of estimated parameters (over-identifying) with the null hypothesis that the instrument is valid. In addition to testing the validity of the instrument variables, this test is also used to see whether the residual data of the GMM estimation is homoscedasticity. The

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value of chi-sq(38) = 11, p-value = 0.99999, indicates H0: The instrument is valid (uncorrelated with the error term). Hence, it is concluded that we fail to reject H0 (instrument is valid). A high p-value indicates no evidence of violation of the instrument assumptions.

c. Unbiasedness Test Results

The unbiasedness criterion is obtained from comparing the GMM dependent lag estimator with FEM (Fixed Effect Model) which is biased downward and PLS (Pooled Least Squares) which is biased upward. The unbiased estimator will be between the FEM and PLS models. The dependent lag coefficients are as follows.

Table 10.
Comparison of SYS-GMM Dependent Lag Coefficients

Estimation	Coefficient Value
FEM	0.61351964
SYS-GMM	0.97258398
PLS	1.00427064

Source: R Studio Data Processing Results

From the comparison of the results above, it shows that the unbiasedness is fulfilled because the SYS-GMM dependent lag coefficient is between FEM and PLS. Therefore, it can be concluded that the best model is the SYS-GMM model.

Selection of the Best Model

The SYS-GMM model is the best model used in this study because it fulfills the parameter significance test and model specification test (consistency test, validity test, unbiased test). The SYS-GMM estimation results can be shown below.

Table 11.
Short-term SYS-GMM Estimation Results

Variable	Estimate	Std. Error	z-value	p-value
lag(log(co2))	0.97258398	0.01693861	57.4182	< 2.2e-16
log(pop)	0.01859580	0.00307809	6.0413	1.528e-09
GDP	0.00221310	0.00279170	0.7927	0.42793
ERG	0.00015355	0.00124142	0.1237	0.90156
HDI	-0.22257947	0.11932634	-1.8653	0.06214

Source: R Studio Data Processing Results

The coefficient of lag(log(co2)) is 0.9726 (significant at 0.1%). There is a strong relationship of the CO_2 emission variable from year to year, a value close to 1 indicates that the current CO_2 emission value is strongly influenced by the previous value. Coefficient log(pop) = 0.0186 (significant at 0.1%), meaning that a 1% increase in population increases CO_2 emissions by about 0.0186% ceteris paribus. Population growth contributes positively to emissions, but the elasticity is small.

The GDP coefficient of 0.0022 is not significant (p-value = 0.428). GDP growth affects CO_2 emissions insignificantly. The insignificant value is due to the Environmental Kuznets Curve (non-linear) effect not captured in the linear model. The coefficient of energy consumption (ERG) = 0.00015 is also insignificant (p-value = 0.902). Energy consumption does not have a significant impact on CO_2 emissions, due to access to renewable energy by the population. While the coefficient of Human Development Index (HDI) = -0.2226, is significant at 10% (p-value = 0.062). Countries with a high HDI tend to have lower CO_2 emissions. People with a good quality of life are more environmentally conscious or have energy efficient technologies.

Variables that are not significant (GDP, ERG) need quadratic transformation for Kuznets curve or other proxy variables. Although the energy consumption variable is not significant, it is still important to prioritize the transition to renewable energy and low-carbon technologies.

Estimation Results in the Long Run

The long-term equation estimation for the SYS-GMM model shows that economic growth, population, energy consumption and Human Development Index affect carbon emissions, the results can be seen in table 12.

Table 12.
Long-term Estimation Results

Variable	CLR SYS-GMM
-lag(log(co2))	0.9725
-log(cld)	0.0278
log(pop)	0.6783
GDP	0.0807
ERG	0.0056
HDI	-8.1186

Source: R Studio Data Processing Results

Effect of Previous Period to Current Period (Dependence)

Based on the table above, the Lag coefficient value (cld = 0.972584), shows CO_2 emissions strongly follow the previous pattern where previous period CO_2 emissions strongly influence and carry over to the current emission period by 97.25%, indicating strong hysteresis. CO_2 emissions are difficult to change drastically in the short term. Policy changes in reducing carbon emissions such as carbon tax and net zero emission policies take a long time to show the full effect.

Speed of Convergence

The value conv = -log(cld) indicates the speed of convergence (conv = 0.0278). With a convergence value of 0.0278, the system takes 1/0.0278 or equal to 36 years to reach equilibrium. It can also be said that only 2.78% of the emission imbalance is corrected each year. The typical value is very slow when compared to typical values in environmental studies of 0.02-0.05, indicating structural inflexibility such as reliance on fossil-based infrastructure and slowing clean technology innovation.

Long-Run Elasticities

In table 4.6 the results in the long-term equation show that every 1% increase in population will increase CO_2 emissions by 0.678%. The value of GDP (0.0807) means that in the long run, every 1% increase in economic growth (GDP) will increase carbon emissions by 0.0807%. The relatively low value may indicate a greener economic structure or an Environmental Kuznets Curve (EKC) effect.

Energy has a positive but very small impact (0.0056). Every 1% increase in energy consumption increases CO_2 emissions by 0.00056. This is a very small number due to increased energy efficiency and a shift to renewable energy. In addition, the data used is also the total overall access to energy by the population in each country of the ASEAN region. HDI (-8.118) shows a large negative coefficient. Every 1% increase in the Human Development Index (HDI) will decrease CO_2 emissions by 8,118. Countries with higher HDI tend to have lower emissions. This reflects people's environmental awareness, stricter environmental policies and more advanced clean technologies.

Effect of Economic Growth (GDP) on CO_2 Emissions

In the short term, economic growth (GDP) has a positive but insignificant effect on CO_2 emissions (p-value = 0.42793). In the long run, the effect of GDP remains positive but very weak (CLR = 0.0807).

This finding is in line with the *Environmental Kuznets Curve (EKC)* and the IPAT model that states that in the early phase of economic development, increasing GDP often increases carbon emissions due to dependence on fossil energy and growth of resource-based industries (see *Chapter II, pp. 15-18*). However, the insignificant effect of GDP in the short term indicates that some ASEAN countries have started to diversify their economies and adopt cleaner technologies, albeit not optimally (see *Musyarof & Qomari, 2023; Liu et al., 2023).

Empirically, this result supports the findings of Musyarof & Qomari (2023) that ASEAN's green economy transformation has not been significant, and Bieth (2020) that GDP in ASEAN countries has a positive but weak effect on CO_2. In the EKC framework, the turning point has not yet been reached because ASEAN's economic sectors are still dominated by carbon-intensive industries.

Effect of Population on CO_2 Emissions

Population (log(pop)) has a positive and highly significant effect on CO_2 emissions in both the short term (coefficient 0.0186; $p < 0.001$) and long term (CLR = 0.6783). This finding is highly consistent with the IPAT model and Malthus' theory (*Chapter II, pp. 19-21*), which states that population growth increases pressure on resources and the environment. Any increase in population, especially in rapidly urbanizing countries (e.g. Indonesia, Philippines, Vietnam), will increase demand for energy, transportation, and consumption of goods, all of which increase carbon emissions. This result is in line with Rofiuddin et al. (2019) and Mahendra et al. (2022) who concluded that population in ASEAN has a positive and significant effect on carbon emissions. In fact, in the long run, the effect becomes cumulative and very dominant.

Effect of Energy Consumption on CO_2 Emissions

Energy consumption (ERG) has a positive, but insignificant effect in both the short term (coefficient 0.00015; p = 0.901) and long term (CLR = 0.0056). Fossil energy consumption should be the main driver of carbon emissions. However, the insignificance of this result is explained by the energy transition, the diversity of energy sources in ASEAN (coal, hydro, geothermal, solar), as well as the inefficiency in measuring total energy consumption that does not distinguish between fossil and renewable. These results differ from those of Shafei & Ruhul (2013), but support the findings of Liu et al. (2023) that energy intensity varies widely and energy consumption is not the only major driver of carbon emissions in Southeast Asia. Countries like Vietnam and Laos are starting to rely on hydropower and solar power, which are relatively more environmentally friendly, so the aggregate effect of energy consumption on emissions is not significant.

Effect of Human Development Index (HDI) on CO_2 Emissions

HDI has a negative and significant effect on CO_2 emissions, especially in the long run (CLR = -8.1186; $p < 0.1$). This finding confirms the importance of human development (education, health, economy) in reducing carbon emissions. Countries with a high HDI tend to have people who are more environmentally conscious, able to adopt low-carbon technologies, and support stricter environmental policies. Empirically, this result supports Hussain & Dey's (2021) research that HDI reduces CO_2 emissions in a panel of developing countries. However, in contrast to Bieth (2020) who found HDI actually increases emissions in certain countries, because the consumption and lifestyle of people with high HDI are not fully environmentally friendly.

CONCLUSION

Based on the results and discussion previously described, several conclusions can be drawn.

1. Economic Growth (GDP) has an insignificant positive effect in the short term but has a weak positive impact in the long term. This means that ASEAN economic growth has not been fully separated from dependence on fossil energy sources. However, in the long run, it indicates a greener economic structure or an Environmental Kuznets Curve (EKC) effect.
2. Population (POP) has a positive and significant effect on CO_2 emissions, both in the short and long term. High population growth will increase the demand for energy and economic activities that have the potential to increase emissions.
3. Energy consumption (ERG) has an insignificant positive effect on CO_2 emissions, due to the diversity of access to energy sources by households and industries, including renewable energy or measurement inefficiencies.
4. Human Development Index (HDI) has a negative and significant effect on CO_2 emissions, especially in the long run. This suggests that improving human quality (through education, health and the economy) can drive the transition to sustainable development and ultimately reduce CO_2 emissions.

Based on the results of the study, several policy suggestions can be made to reduce CO_2 emissions in the ASEAN region, including:

1. Controlling Population Impacts

Controlling population impacts can be done by encouraging low-carbon urban planning such as mass public transportation and city development, strengthening family planning programs and environmental awareness to reduce population pressure on resources.

2. Strengthening Sustainable Human Development

Improve access to environmental education and green skills training to encourage environmentally friendly behavior, integrate green economy principles in development policies (e.g. incentives for green industries).

3. Decarbonize Economic Growth

Encourage investment in renewable energy (solar, wind, hydro) to decouple economic growth from fossil emissions, impose a carbon tax to encourage energy efficiency in the industrial sector, improve energy efficiency through energy-efficient building and equipment standards.

4. Long-term Strategy

Establish an ASEAN regional framework for monitoring and targeting emission reductions, for example through an ASEAN Green Deal similar to the EU's European Green Deal, and strengthen cooperation with developed countries on low-carbon technology transfer and climate finance.

A holistic approach is needed due to the complex interactions between population, economy and human quality, not only reducing emissions, but also considering social equity, green economy and cross-sector policies. Accelerating technological innovation is key to achieving economic growth without increasing emissions. With integrated policy implementation, ASEAN can achieve sustainable development goals (SDG's) while contributing to global climate change mitigation.

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