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Analysis of The Effect of Energy Consumption, Economic Growth, And Trade Openness on Carbon Emissions: A Case Study of Indonesia 2003-2023

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ABSTRACT

This study aims to analyze the influence of energy consumption, economic growth, and trade openness on carbon emissions in Indonesia. The research issue arises from the significant increase in Indonesia's carbon emissions over the past two decades, which has contributed to climate change, environmental degradation, and various sustainability challenges. As one of the developing countries with rapid economic growth, Indonesia faces the dual challenge of maintaining economic expansion while reducing environmental pressure. To address this issue, the study applies a quantitative approach using the Partial Adjustment Model (PAM) regression technique to examine the dynamic relationship between the selected variables. The analysis is based on annual time series data from 2003 to 2023, obtained from credible sources such as Statistics Indonesia (BPS), the World Bank, and the International Energy Agency (IEA). The findings reveal that energy consumption has a negative and statistically significant effect on carbon emissions, indicating an improvement in energy efficiency and a gradual transition towards renewable energy sources. Meanwhile, economic growth has a positive and significant impact on carbon emissions, suggesting that Indonesia's economic activities remain highly dependent on fossil fuels. In contrast, trade openness shows a positive but insignificant effect on carbon emissions. Overall, the study underscores the urgent need for integrated policies promoting green energy transition, sustainable trade, and low-carbon economic strategies to achieve environmentally responsible and sustainable long-term growth in Indonesia.

Keywords: *Carbon Emissions, Energy Consumption, Trade Openness, Economic Growth, PAM*

ABSTRAK

Penelitian ini bertujuan untuk menganalisis pengaruh konsumsi energi, pertumbuhan ekonomi, dan keterbukaan perdagangan terhadap emisi karbon di Indonesia. Permasalahan penelitian ini muncul dengan adanya peningkatan emisi karbon secara signifikan dalam dua dekade terakhir, yang telah memberikan dampak serius terhadap perubahan iklim, kerusakan lingkungan, serta menimbulkan tantangan besar bagi keberlanjutan pembangunan ekonomi nasional. Sebagai salah satu negara berkembang dengan laju pertumbuhan ekonomi yang tinggi, Indonesia menghadapi dilema antara mempertahankan ekspansi ekonomi dan menekan tekanan terhadap lingkungan. Untuk menjawab permasalahan tersebut, penelitian ini menggunakan pendekatan kuantitatif dengan metode regresi Partial Adjustment Model (PAM) guna menganalisis hubungan dinamis antarvariabel penelitian. Analisis dilakukan menggunakan data runtut waktu (time series) tahunan dari tahun 2003 hingga 2023 yang diperoleh dari berbagai sumber terpercaya, seperti Badan Pusat Statistik (BPS), World Bank, dan International Energy Agency (IEA). Hasil penelitian menunjukkan bahwa konsumsi energi berpengaruh negatif dan signifikan terhadap emisi karbon, yang menandakan adanya peningkatan efisiensi energi serta pergeseran menuju penggunaan energi terbarukan. Sebaliknya, pertumbuhan ekonomi berpengaruh positif dan signifikan terhadap emisi karbon, menunjukkan bahwa aktivitas ekonomi nasional masih sangat bergantung pada energi fosil. Adapun keterbukaan perdagangan memberikan pengaruh positif namun tidak signifikan terhadap emisi karbon. Secara keseluruhan, penelitian ini menegaskan pentingnya kebijakan transisi energi, efisiensi energi, serta perdagangan hijau yang mendukung pertumbuhan ekonomi berkelanjutan dan rendah karbon di Indonesia.

Kata Kunci: *Emisi Karbon, Konsumsi Energi, Keterbukaan Perdagangan, Pertumbuhan Ekonomi, PAM*

1. Introduction

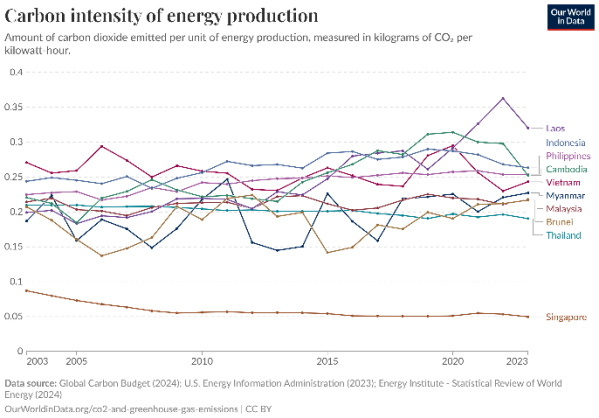
Due to decades of neglect, climate change and environmental degradation have emerged as two of the most pressing issues facing the world today. Where the main contributor to global warming and climate change is carbon dioxide ($CO^{2)}$emissions which are increasing significantly as temperatures rise. Various factors play a role in increasing temperatures, both at the national and global levels, with carbon emissions being one of the main contributors to greenhouse gases. Most of these emissions are produced by human activities in daily life, especially through combustion processes such as those that occur in power plants and industrial activities (Hakim et al., 2025).

According to Prinadi et al. (2022) The significant increase in carbon dioxide emissions in the last decade is caused by human activities. Population growth drives an increase in demand for goods and services, which in turn stimulates economic activity. In this context, companies seek to meet market needs by expanding their production capacity or opening new businesses, thereby driving

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economic growth. However, the expansion of economic activity is often accompanied by an increase in fossil-based energy consumption, which is a major source of carbon dioxide emissions. On the other hand, increased trade openness also contributes to the intensification of production and distribution activities across countries, which can accelerate the flow of goods but at the same time increase the global carbon footprint (Pratama, 2021).

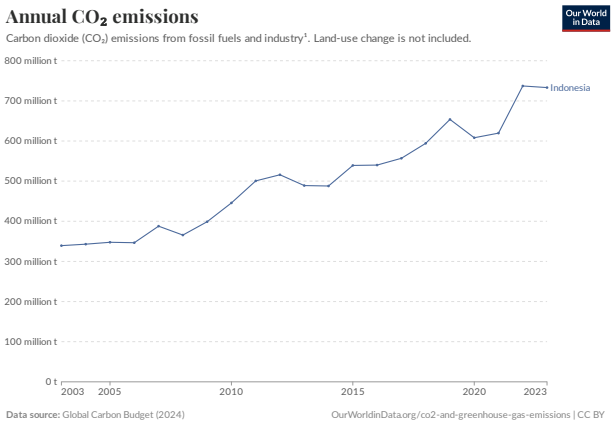
Thus, both economic growth and trade openness have a close relationship with the increase in carbon emissions that have an impact on climate change and environmental damage. As a developing country with the largest economy in Southeast Asia, Indonesia is faced with similar challenges (Zahra & Aryati, 2023) .



Source1 : Processed from Global Carbon Budget data (2024)

As a developing country with the largest economy in Southeast Asia, Indonesia is faced with similar challenges. Indonesia is one of the countries that has a high concentration of carbon dioxide emissions. According to the IEA report in 2023, Indonesia is also one of the countries with the highest CO2 emissions (Perwithosuci et al., 2024) . Indonesia seeks to improve the welfare of its people through economic development. However, economic development is usually accompanied by an increase in energy use, the majority of which is sourced from fossil fuels, namely gas, oil and coal. This increase in energy use directly contributes to the rise of carbon emissions in Indonesia. The country's energy use continues to grow in line with the industrialization process and population growth, according to data from the Ministry of Energy and Mineral Resources.

According to Ritchie & Roser(2020) from source 1 Compared to other ASEAN countries, the carbon intensity of energy production in Indonesia is still high. This reflects a heavy reliance on fossil energy sources, particularly coal, which is the main contributor to carbon emissions in the national energy sector. While some countries such as Malaysia and Thailand have shown better energy efficiency, Indonesia is still at an intermediate level in emission reduction efforts. On the other hand, Singapore and Brunei have successfully reduced carbon intensity through the utilization of clean energy and the application of more efficient technologies. This shows the need to accelerate the energy transition in Indonesia towards renewable energy sources to support low-carbon and sustainable development.



Source2 : Processed from Global Carbon Budget data (2024)

Economic growth, and the openness of international trade affect the level of carbon dioxide emissions. Traditionally, an increase in CO_2 emissions is often followed by higher economic growth. This condition occurs because conventional economic growth models tend to ignore environmental aspects in the development process (Hidayah et al., 2023) . The trend of Indonesia's carbon emissions over the period 2003 to 2023 shows a consistently increasing trend, with some minor fluctuations. At the beginning of the period in 2003, carbon emissions were around 339,357 metric tons per capita, and increased to around 733,224 metric tons per capita in 2023. This increase reflects rapid economic growth, increased energy demand, and the dominant dependence on fossil fuels. This phenomenon is in line with the findings of (N. Stern, 2007) which explains that carbon emissions in developing countries tend to increase along with economic growth and industrialization, as energy-intensive sectors such as manufacturing, transportation, and construction increasingly dominate the economic structure. Similarly, Purnomo et al.(2023) noted that in Indonesia, fossil-based energy consumption is a major contributor to carbon emissions, especially in the industrial and transportation sectors.

According to Ritchie & Roser(2020) Compared to other ASEAN countries, the carbon intensity of energy production in Indonesia is still relatively high. This reflects a heavy reliance on fossil energy sources, particularly coal, which is a major contributor to carbon emissions in the national energy sector. While some countries such as Malaysia and Thailand have shown better energy efficiency, Indonesia is still at an intermediate level in emission reduction efforts. On the other hand, Singapore and Brunei have managed to reduce carbon intensity through the utilization of clean energy and the application of more efficient technologies. This shows the need to accelerate Indonesia's energy transition towards renewable energy sources to support low-carbon and sustainable development.

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Furthermore, trade openness is a major component in influencing carbon emissions. International trade has become a major source of national economic development in the current globalization (Puspita & Hartono, 2021) . However, trade openness can lead to increased carbon emissions through the production of goods to be exported and the import of goods made with environmentally unfriendly processes. Previous research has investigated the relationship between economic growth, trade openness energy consumption, and carbon emissions. Existing studies found that there is a correlation between trade openness and increased carbon emissions. The studies show that these factors have a significant impact on a country's carbon emission levels. For example, according to research conducted by Siregar & Hasbi(2023) , economic growth has a positive impact on carbon dioxide emissions in the long run, while energy consumption and trade openness have no significant impact in the short or long run. However, according to Adrian (2024) trade openness and population expansion contributed less to the increase in carbon emissions in Indonesia than the increase in energy consumption caused by economic and community growth. Deforestation and population expansion appear to have no impact, although increases in energy consumption and gross domestic product do.

Theoretically, the relationship between economic growth and carbon emissions is explained by the Environmental Kuznets Curve (EEKC) introduced by Grossman and Krueger in 1991. The theory suggests that at the beginning of economic growth, increased production and industrialization drive up carbon emissions (Fildzah & Handoyo, 2025) . However, after reaching a certain income, emissions tend to fall as people and governments switch to green technologies, improve energy efficiency, and tighten environmental regulations (Aynun zubaydah, 2024) . EKC provides an important conceptual framework for understanding the interaction between economic development and environmental impacts in developing countries such as Indonesia, which is in a phase of industrialization and economic expansion (Hasid et al., 2022) .

In terms of policy, Indonesia has pledged to reduce carbon emissions by 31.89% through independent efforts and up to 43.20% with international assistance by 2030, according to the Enhanced Nationally Determined Contribution (NDC) approved in 2022 by the Ministry of Environment and Forestry (MoEF) . In addition, Indonesia targets Net Zero Emission (NZE) by 2060 or earlier, in accordance with the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (Hermawan & Prabhawati, 2024) . This commitment requires a major shift towards clean energy, improved energy efficiency, and policy reforms in the industrial and trade sectors. Therefore, an in-depth understanding of the economic factors affecting carbon emissions is crucial to formulate effective mitigation strategies that are in line with Sustainable Development Goals (SDGs) point 13 on Climate Action (Haptari, 2023) .

To address this issue, Indonesia must take sustainable action to control carbon emissions without halting economic growth. Increasing the use of renewable energy and energy efficiency in various sectors, as well as implementing more environmentally friendly trade policies, are important steps that can be taken. Indonesia also needs to strengthen carbon emission regulations and encourage industries to adopt more sustainable practices. In this context, this study aims to examine how trade openness, economic growth and energy consumption affect carbon emissions in Indonesia. The selection of the 2003-2023 timeframe is based on the availability of more complete and consistent data, and includes various dynamics of energy policy, trade, and national economic development that are relevant for analysis. It is hoped that this research can provide an empirical basis for policy formulation that balances economic growth and environmental protection, while clarifying the main factors that influence carbon emissions.

2. Theoretical foundation

Theoretical concept of energy consumption

Energy is very important for a country's economy because fossil fuels are still the main energy used in economic activities. However, the increase in energy consumption in developed and developing countries has caused problems such as a decrease in the availability of energy resources, especially petroleum, and increased global warming due to greenhouse gas emissions such as carbon dioxide (CO2) (S et al., 2019) . Energy has a crucial role in supporting economic activities to meet consumption needs and assist the production process in various industrial sectors. In addition to functioning as a consumption good, energy is also an important element in the development and advancement of technology that has a significant impact on economic growth (Pratiwi, 2021) .

Energy consumption and carbon emissions are closely related. The research above describes a two-way causality relationship between energy consumption and carbon dioxide emissions, when energy consumption increases, especially from non-renewable sources (such as fossil fuels), CO2 emissions tend to increase, and conversely, increased emissions can affect energy consumption policies. Research from Adrian (2024) shows that increased energy consumption due to economic and social development is the main cause of rising carbon emissions in four ASEAN countries. Meanwhile, another study by Regina Citra Kurnia Pangestu & Anak Agung Ketut Ayuningsasi ,(2024) found that in Indonesia, carbon emissions increased mainly due to household energy consumption, as well as the dependence of the industrial and transportation sectors on non-renewable energy.

Economic growth theory

Economic growth is the process of increasing a country's ability to produce goods and services in a sustainable manner. which is reflected in the increase in real GDP and increased productivity and welfare of society (Liana et al., 2024) . Economic growth is a

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measure of success in the development of a nation. Development that is shown to improve welfare and create a just society is part of the development process. Therefore, the right approach needs to be applied in development to encourage economic growth while maintaining justice (Amdan & Sanjani, 2023) . In practice, increasing economic growth to improve people's welfare is the main goal of developing countries. This is due to the fact that the faster the economic growth, the more capable a country is to provide for its citizens (Larasati & Utomo, 2023) .

Factors that influence economic growth include investment, labor, technology, government policies, and international market conditions (Veronica & Sari, 2024) . One of the terms often used to describe a country's economy is its growth rate. In Adam Smith's classical economic theory, economic growth is determined by two main elements, namely the increase in total output and population growth. The increase in the country's productivity can be seen from the increase in output, while the increase in population in the context of the increasing purchasing power and consumption of individuals in society. In neoclassical theory, however, output growth is considered to be the result of an increase in various factors, including an increase in the quantity and quality of output. (Rahmandani & Dewi, 2023) .

Ha1: It is suspected that energy consumption has a significant effect on carbon emissions in Indonesia.
Ha2: It is suspected that economic growth has a significant effect on carbon emissions in Indonesia.
Ha3 It is suspected that trade openness has a significant effect on carbon emissions in Indonesia.

Research results from Widyawati et al.(2021) explain that countries with developing economies produce much lower carbon dioxide emissions. This shows that CO_2 emissions tend to decrease as economic activity increases. One possible explanation is that nations experiencing rapid economic growth are better equipped to implement green development programs, which in turn result in lower carbon dioxide emissions (Sauki & Sudihartono, 2023) . In contrast, according to Perwithosuci et al.(2024) found different results, namely in the short term economic growth increases CO_2 emissions, while in the long term it decreases them. This finding confirms that the relationship between economic growth and carbon emissions is complex and influenced by time and development policies.

Trade openness theory

Trade openness occurs when a country is willing to trade with other nations through exporting or importing goods and services, as well as receiving foreign investment. Supportive policies include reduced import taxes, removal of restrictions on the quantity of goods, or free trade agreements. The more open a country is to international trade, the stronger its connection to the global economy. According to Ifa et al.(2020) since international trade and economic growth drive economic growth in the long run, they go hand in hand. A country's GDP grows faster in proportion to its level of trade. Therefore, trade is very important for a country's economic development, and its significance is increasingly evident along with economic growth in most countries.

The results of Wulandari Siregar & Hasbi (2023) show that trade openness and energy consumption have no significant effect on carbon dioxide emissions, either in the short or long term. However, economic growth has a positive impact on carbon dioxide emissions in the long run. Relevant to the previous study, research conducted by Widyawati et al. (2021) found that international trade openness has a negative impact on carbon dioxide emissions. The more open a country is, the lower its carbon emissions. This happens because countries focus on industries or sectors with relative advantages, utilizing optimal resources for the welfare of the population. With increased welfare, the government implements stricter environmental regulations, thus motivated to reduce carbon dioxide emissions.

Variables and Hypotheses

In this study, several variables are applied to explain the Research Analysis of the Effect of Energy Consumption, Economic Growth, and Trade Openness on Carbon Emissions in Indonesia. The variable that explains the influence of the independent variable is carbon emissions ($CO_{2)}$, while the variable energy consumption, economic growth, and trade openness will be the independent variable that affects the dependent variable (carbon emissions). the hypotheses proposed in this research are:

The hypothesis is based on empirical evidence from previous studies that are reviewed to describe the correlation between the dependent variable and the independent variable and its impact on the environment. This study also aims to provide an understanding of the factors affecting carbon (CO2) emissions in Indonesia and their implications for environmental policy and sustainable economic development.

3. Methodology

This study analyzes the effect of energy consumption, economic growth, and trade openness on carbon emissions in Indonesia. This study uses annual data from 2003 to 2023. Indonesia was chosen because it faces challenges in balancing economic growth and the environment. In this study, an econometric model adapted from the Partial Adjustment Model (PAM) is used, as this model is able to capture both short-term and long-term adjustments simultaneously, making it more suitable than ordinary time series regression models. This model was developed and used by the researcher. The following is the econometric equation model:

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$$logCO^2{}_t = \delta\beta_0 + \delta\beta_1 EN_t + \delta\beta_2 GDP_t + \delta\beta_3 TRD_t + (1-\delta) logCO^2{}_t + \varepsilon_t \quad (1)$$

Where:

CO^2	: Carbon emission (million tons ($MtCO_2$))
EN	: Energy consumption (gigajoules (GJ(%))
GDP	: Economic growth (%)
TRD	: Trade openness (%)
δ	: adjustment coefficient
β_0	: constant
$\beta_1, \beta_2, \beta_3$	: coefficient of independent variable
$1-\delta$	: previous period CO^2coefficient
ϵ_t	: Error term.
t	: year t

The variableCO_2 represents the level of carbon emissions measured in metric tons per capita, reflecting the environmental impact of economic activity and energy consumption. **EN**, or energy consumption, is expressed in gigajoules (GJ), measuring the total energy used in various sectors. **GDP**, as an indicator of economic growth, is expressed in annual percentage change and is used to reflect a country's level of economic development. Furthermore, **TRD**, or trade openness, also expressed as a percentage, measures the proportion of international trade to gross domestic product (GDP), thus reflecting a country's economic integration in global trade. In addition, this study takes into account **ϵt**, an error term, which represents other factors that are not captured by the model but may affect the results of the analysis. This combination of variables is designed to evaluate the causal and dynamic relationship between economic factors, energy consumption and its impact on carbon emissions, particularly in the context of the Indonesian economy.

3.1 Data

This study uses time series data consisting of a time span of twenty years, from 2003 to 2023. The type of data used is secondary data, which is data that has been collected and published by official institutions, so it has a high level of reliability and validity. The use of secondary data was chosen because it allows researchers to obtain information that is consistent, comparative, and relevant to the research topic over a long period of time.

The data collected includes the main variables analyzed in this study, such as energy consumption, economic growth, trade openness, and carbon emissions in Indonesia. Each variable is taken from credible and internationally recognized sources, including:

1. Central Bureau of Statistics (BPS): to obtain data on economic growth (GDP).
2. World Bank: to obtain trade openness data.
3. International Energy Agency (IEA) - for data related to energy consumption and carbon emissions on an annual basis.

All data obtained was then processed and adjusted in uniform units so that it could be analyzed comparatively. Data processing included data cleaning, time series formatting, and data transformation where necessary, to ensure accurate and reliable statistical analysis.

3.2 Analysis Method

The analytical method used in this study is the *Partial Adjustment Model* (PAM). This model is used to describe the partial adjustment process of a dependent variable to its equilibrium value in the long run. In the context of this study, the dependent variable analyzed is carbon dioxide (CO_2) emissions, while the independent variables include energy consumption, economic growth, and trade openness.

The PAM method was chosen because this model is suitable for analyzing time series data, which is data arranged in time sequence over the period 2003 to 2023. Time series data often show changes that do not lead directly to equilibrium, but through a gradual adjustment process over time. As such, PAM is appropriate for understanding how changes in these economic variables affect carbon emission levels, both in the short and long term.

This Partial Adjustment model assumes that any change in the independent variable does not necessarily cause the dependent variable to reach its equilibrium level in the same period. Instead, these changes occur gradually due to economic, social and structural adjustment factors in a country. Through this approach, the research can identify the speed of adjustment and the magnitude of the long-term influence of each variable on carbon emissions.

The analysis was conducted using linear regression method with *Ordinary Least Squares* (OLS) approach to estimate the relationship between variables. Before the estimation process, the data was first tested through several stages such as stationarity test, autocorrelation test, heteroscedasticity test, and multicollinearity test. This stage is important so that the model estimation results can fulfill classical assumptions and produce valid conclusions that can be scientifically justified.

4. Results and Discussion

4.1 Results

Based on the econometric equation (1), the econometric estimation results are as follows:

Table 1
Econometric Model Estimation Results

$\widehat{logCO^2}_t = 3.5055 - 0.0149 EN_t + 0.0190 GDP_t -$ (0,0198) (0,0314) $0.0019 TRD_t + 0.51123 logCO^2{}_{t-1}$ (0,5185) (0,0085)
$R^2 = 0.9659$; $DW - stat = 1.8993$; $F - stat = 106.2352$; $prob\ F - stat = 0.0000$
Diagnosis test: 1. Multicollinearity Test (VIF) Energy Consumption (EN)= 15.3204; GDP= 1.48774; TRD= 4.53478 2. Residual Normality Test (Jarque Bera)

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	JB(2)= 2.0838; Prob JB(2)= 0.35277
3.	Autocorrelation Test (Breusch-Godfrey) $x^2 = 0.73067; Prob\ x^2 = 0.694$
4.	Heteroscedasticity Test (White) White no Cross Term $x^2 = 6.44222; Prob\ x^2 = 0.5978$
5.	Model Specification Test (Ramsey Reset) F(1,14) = 0.5332; Prob(1,14) = 0.4773

Source: processed data

$1 - \ \delta = 0.5112$

$\delta = 1 - 0.5112 = 0.4888$

1) $\alpha_0 = \delta\beta_0$

$3.5055 = 0.4888$

$\beta_0 = \frac{\delta\beta_0}{\delta} = \frac{3.5055}{0.4888} = 7.1716$

2) $\alpha_1 = \delta\beta_1$

$-0.1049 = 0.4888$

$\beta_1 = \frac{\delta\beta_1}{\delta} = \frac{-0.1049}{0.4888} = -0.0304$

3) $\alpha_2 = \delta\beta_2$

$0.0190 = 0.4888$

$\beta_2 = \frac{\delta\beta_2}{\delta} = \frac{0.0190}{0.4888} = 0.0388$

4) $\alpha_3 = \delta\beta_3$

$-0.0019 = 0.4888$

$\beta_3 = \frac{\delta\beta_3}{\delta} = \frac{-0.0019}{0.4888} = -0.00388$

From the measurement of constants and coefficients, a long-run estimation model is obtained as follows:

$$logCO^2{}_t = 7.1716 - 0.0304EN_t + 0.0388GDP_t - 0.00388TRD_t$$

With Adjustment time:

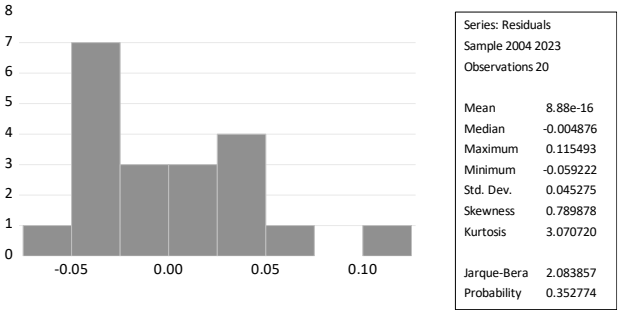
$AT = \frac{1}{0.4888} = 2{,}045\ tahun$

4.2 Discussion

The results of the estimated econometric model and its complementary tests are summarized in Table 1.

This study uses a Partial Adjustment Model (PAM) approach to forecast energy consumption, economic development and trade openness in relation to carbon emissions in Indonesia from 2003 to 2024. In Table 1, you can see the results of the PAM calculation and the classical assumption test. For CO2 from the previous year (1 - δ), the regression coefficient value is 0.51123. As seen from the t-statistic probability <0.05, the PAM is valid under this condition. The study model meets the validity requirements of PAM, which allows it to display the theoretical relationship between the dependent and independent variables, both in the short run and long run.

Figure1 Normality Test (Jarque-Bera)



H_o: Residuals are normally distributed
H_a: Residuals are not normally distributed

The findings of the Jarque-Bera (JB) Test describe the probability of the JB statistic, which is 0.35277 greater than the significance level (α = 0.1) so that $H_o$is accepted. Thus, it can be concluded that the residuals in this regression model are normally distributed, so the classical assumption of normality is fulfilled.

Table 2. Autocorrelation Test (breusch-Godfrey)

F-statistic	0.246472	Prob. F(2,13)	0.7851
Obs*R-squared	0.730670	Prob. Chi-Square(2)	0.6940

H_o: there is no autocorrelation problem
H_a: there is an autocorrelation problem

Furthermore, the Breusch-Godfrey (BG) Test results show that the probability value of the Chi-Square statistic (χ^2) is 0.694, which is greater than the significance level (α = 0.1). Thus, it can be concluded that there is no autocorrelation problem in the regression model used. This indicates that the residuals of the model are independent of each other, or in other words, the error value in a certain period is not influenced by the error value in the previous period.

Table 3. Heteroscedasticity Test (white)

F-statistic	0.653357	Prob. F(8,11)	0.7213
Obs*R-squared	6.442229	Prob. Chi-Square(8)	0.5978
Scaled explained SS	3.751890	Prob. Chi-Square(8)	0.8788

H_o: there is no heteroscedasticity
H_a: heteroscedasticity occurs

The findings of the White's test show that the probability value of the Chi-Square statistic (χ^2) is 0.5978, which is greater than the significance level (α = 0.1). Thus, it can be concluded that there is no heteroscedasticity problem in the estimated regression model. This result indicates that the variance of the residuals is constant or homogeneous across observations, so the model fulfills the assumption of homoscedasticity. The absence of heteroscedasticity indicates that error fluctuations do not depend on the value of the independent variable, which means that the model has good residual variance stability.

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Table 4. Model Specification Test

	Value	df	Probability
t-statistic	0.730218	14	0.4773
F-statistic	0.533218	(1, 14)	0.4773
Likelihood ratio	0.747592	1	0.3872

H_o: the estimated model is exact or linear
H_a: the estimated model is not exact or linear.

The model specification test results show that the probability value of the F statistic is 0.4773, which is greater than the significance level (α = 0.1). Based on these results, it can be concluded that the model used has been estimated correctly and is linear. This means that the model specification does not experience *functional form misspecification,* so that the relationship between the independent variable and the dependent variable is in accordance with the basic assumptions of the linear regression model.

Table 5. Variance Inflation Factors (VIF) Test

Variable	Coefficient Variance	Uncentered VIF	Centered VIF
C	1.415282	10901.47	NA
EN	3.28E-05	248.7190	15.32047
GDP	6.47E-05	13.78055	1.487748
TRD	8.93E-06	157.0184	4.534781
LOG(CO2(-1))	0.028487	8362.158	12.12384

H_o: there is no multicollinearity between independent variables
H_a: there is multicollinearity between independent variables

The multicollinearity test results show that the Economic Growth (GDP) and Trade Openness (TRD) variables have a Variance Inflation Factor (VIF) value of less than 10, which means that the two variables do not experience multicollinearity problems. This condition indicates that the relationship between independent variables is relatively weak, so that each variable is able to explain the dependent variable independently without influencing each other excessively.

However, it is different with the Energy Consumption (EN) variable which shows a VIF value exceeding the tolerance limit (VIF> 10). This indicates a multicollinearity problem in the variable. In other words, Energy Consumption has a strong enough relationship with one or more of the other independent variables in the model. This condition can cause the regression coefficient to be unstable, the standard error to increase, and the significance test to be inaccurate.

Table 6. F-test and R-square

R-squared	0.965904	Mean dependent var	6.207341
Adjusted R-squared	0.956812	S.D. dependent var	0.245196
S.E. of regression	0.050956	Akaike info criterion	-2.903397
Sum squared resid	0.038947	Schwarz criterion	-2.654464
Log likelihood	34.03397	Hannan-Quinn criter.	-2.854803
F-statistic	106.2352	Durbin-Watson stat	1.899302
Prob(F-statistic)	0.000000		

The F-test results show that the probability value of the F-statistic is 0.000, which is smaller than the significance level α = 0.05. Based on these results, it can be concluded that simultaneously the variables of energy consumption (EN), economic growth (GDP), and trade openness (TRD) have a significant effect on carbon emissions (CO_2) in Indonesia. This means that the three independent variables together have a strong ability to explain variations in changes in carbon emissions during the study period.

In addition, the coefficient of determination (R^2) of 0.9659 indicates that 96.59% of the variation in carbon emissions can be explained by the variables of energy consumption, economic growth, and trade openness, while the remaining 3.41% is influenced by other factors outside the model, such as environmental policies, clean energy technology innovation, urbanization levels, or changes in people's consumption patterns. The high R^2 value indicates that the model used has very good *explanatory power*, so the estimation results can be considered representative in describing the relationship between economic activity and carbon emissions in Indonesia.

Table 7. short-term coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	3.505526	1.189656	2.946671	0.0100
EN	-0.014936	0.005731	-2.606371	0.0198
GDP	0.019090	0.008041	2.374040	0.0314
TRD	-0.001975	0.002988	-0.661159	0.5185
LOG(CO2(-1))	0.511231	0.168780	3.028982	0.0085

Table 8. long-run coefficients

Variable	coefficient
c	7.1716
EN	-0.0304
GDP	0.0388
TRD	-0.00388

Referring to Tables 8 and 9, it can be seen that the coefficients that have significance are$\delta\beta 1$ and$\delta\beta 2$, so the variables that significantly contribute to carbon emissions are energy consumption and economic growth, while trade openness has no significant effect. Energy consumption shows a short-term regression coefficient of -0.0149 and a long-term regression coefficient of -0.0304. It can be indicated that there is a significant relationship between the energy consumption variable and carbon emissions with a logarithmic-linear (log-lin) relationship pattern, carbon emissions decrease by 1.49% directly and 3.04% in the long run for every 1% increase in energy

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consumption. On the other hand, carbon emissions rise by 1.49% immediately and 3.14% in the future for every 1% decrease in energy consumption.

Gross Domestic GDP has a short-term regression coefficient of 0.0190 and a long-term coefficient of 0.0388 There is a correlation between the *Gross Domestic* GDP variable and carbon emissions with a logarithmic-linear (log-lin) relationship pattern, so if *Gross Domestic* GDP increases by one percent, carbon emissions increase by 1.90% in the short term, and 3.88% in the long term. Conversely, if *Gross Domestic* GDP decreases by one percent, carbon emissions decrease by 1.90% in the short term and 3.88% in the long term.

Trade openness has a short-term regression coefficient of 0.0019 and a long-term coefficient of 0.0038 There is a correlation between the variable trade openness and carbon emissions with a logarithmic-linear (log-lin) relationship pattern, so if trade openness increases by one percent, carbon emissions increase by 0.19 percent in the short term, and by 0.38 percent in the long term. However, if Trade openness decreases by one percent, carbon emissions decrease by 0.19 percent in the short run and 0.38 percent in the long run.

Negative and significant relationship of energy consumption on carbon emissions. This shows that an increase in energy consumption is followed by a decrease in carbon emissions, both in the short and long term. These findings may mean that energy consumption patterns in Indonesia may have shifted towards more efficient or environmentally friendly energy, for example, the policy of Minimum Energy Performance Standards (MSPs) and energy-saving labels (LTHEs) on household appliances has been strengthened and expanded, including an updated MSP for air conditioners that reportedly saves energy and reduces CO_2 emissions (Antara, 2023) . In addition, energy efficiency actions combined with the transition to renewable energy and energy management in the industrial and building sectors (as stipulated in PP No. 33/2023) also support the reduction of carbon intensity (Ministry of Energy and Mineral Resources, 2024) . This combination indicates that the government's energy efficiency and energy management programs not only increase energy consumption (due to more use), but also reduce emissions simultaneously, so the negative findings are in line with current government policies that prioritize efficiency and sustainability. In line with research by Pangestu & Ayuningsasi(2024) from 1990 to 2021, carbon emissions in Indonesia decreased significantly due to energy use in the transportation and industrial sectors, but increased significantly due to energy consumption in the residential sector. This is not relevant to the study conducted by Salsabila Nur Amalina et al.(2023) which states that there is a positive and statistically significant relationship between consumption and carbon dioxide emissions, both based on short-term and long-term estimates (95 percent confidence level). This is due to the fact that fossil fuels still play an important role in society and the economy, and that increased use of these fuels can result in higher GDP per capita.

Furthermore, Gross Domestic Product (GDP) has a positive and significant effect on carbon emissions. As a result, greater economic growth is usually followed by an increase in carbon emissions. This result is consistent with the *Kaya Identity* theory which states that four main factors determine a country's carbon emissions: population, per capita income level, energy intensity, and carbon intensity of the energy used. In other words, when economic growth (GDP) increases, energy consumption also tends to increase which causes carbon emissions to increase, especially when the energy used is still dominated by fossil-based energy sources. However, according to D. Stern(2003) Carbon emissions show a strong correlation with Gross Domestic Product. Since 1850, about 70% of the total CO2 emissions generated by energy activities came from the United States and Europe, while developing countries are predicted to contribute the most to the increase in carbon emissions in the future, this is because developing countries will now experience a faster increase in population and GDP, as well as growing industries. This study is also relevant to the findings of Prinadi et al.(2022) which outlines a positive relationship between economic growth and increased carbon emissions in a number of ASEAN countries. These results are in line with other studies that confirm the *Environmental Kuznets Curve (EKC)* hypothesis, which states that in the early phase of economic development, an increase in growth will lead to an increase in carbon emissions due to high dependence on fossil energy and industrial activities. However, as per capita income and environmental awareness increase, countries could potentially switch to cleaner and more efficient technologies, which could reduce carbon emissions in the long run. Thus, the relationship between economic growth and carbon emissions is not only linear, but follows an inverted U-shape as described in the Kuznets hypothesis.

Meanwhile, trade openness also has a positive and significant effect on carbon emissions. This means that the more open a country's international trade is, the greater the level of carbon emissions. This result shows that trade openness still relies on fossil or carbon-intensive energy and continues to dominate Indonesia's trade openness. This finding is relevant to the study conducted by Wang & Zhang(2021) , which found that open trade has an influence on carbon emissions. This contradicts the study conducted by Mahmood et al. (2019), which revealed that open trade has no impact on carbon emissions. This implies that the level of trade openness does not directly trigger an increase in carbon emissions.

5. Conclusion

Influence of energy consumption

the research outlines that energy consumption has a negative and significant impact on carbon emissions in Indonesia, both in the near and long term. This indicates that although energy consumption is increasing, Indonesia is shifting to more efficient and environmentally friendly energy utilization, so carbon emissions are not necessarily rising. To strengthen this trend, the government can expand incentives for industries that implement energy

efficiency, accelerate the use of energy-efficient technologies in the manufacturing and transportation sectors, and increase investment in renewable energy such as solar power and biomass.

Effect of economic growth (GDP)

Economic growth contributes positively and significantly to carbon emissions, indicating that increased economic activity is still dependent on fossil energy use. Thus, high economic growth has the potential to increase carbon emissions if not accompanied by good environmental policies. Therefore, policies that encourage low-carbon economic growth are needed, such as encouraging *green industry*, tightening emission standards in the industrial and transportation sectors, and expanding the implementation of carbon taxes or emission trading schemes to control environmentally unfriendly economic activities.

Effect of trade openness

The variable Trade openness has a positive but insignificant effect on carbon emissions. Despite the increase in international trade activities, its impact on carbon emissions is still relatively small, although there are indications that trade openness can increase emissions if not supported by environmentally friendly policies. Therefore, the government needs to ensure that import and export products meet environmental standards, tighten regulations on export-oriented industries to implement green production practices, and optimize trade cooperation that supports clean technology and low-carbon investment.

Overall, energy consumption, economic growth and trade openness have a significant influence on carbon emissions in Indonesia, with the coefficient of determination (R^2) reaching 96.59%. This suggests that most of the variation in carbon emissions in Indonesia can be explained by these three variables.

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