

## The Effects of Gross Domestic Product, Energy Consumption, Urbanization, and Trade Openness on CO<sub>2</sub> Emissions in Indonesia

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The rapid adoption of Artificial Intelligence (AI) is transforming industries and redefining the global job market. In Malaysia, university students preparing to enter the workforce face growing uncertainty about how AI will impact their future careers. While AI brings opportunities for innovation and job creation, it also introduces challenges such as skill gaps, job displacement, and the need for continuous adaptation. According to the World Economic Forum (2023), an estimated 44% of workers' skills will be disrupted within the next five years due to technological changes, emphasizing the urgency for future talent to be prepared. However, limited research has explored how university students perceive AI's impact on employment and whether they feel equipped to meet the demands of this evolving landscape. This study aims to examine the relationship between perceived AI adoption and perceived skill preparedness on students' perceptions of future job market dynamics. Using a quantitative approach, this study provides insights to inform curriculum design, career services, and workforce development strategies that align with the realities of an AI-integrated economy

**Keywords:** CO<sub>2</sub> Emissions; GDP per Capita; Energy Consumption; Environmental Kuznets Curve; Indonesia; Trade Openness; Urbanization

## **INTRODUCTION**

Indonesia has recorded fairly consistent economic growth over the past two decades. Average annual GDP growth reached 4.90% between 2000 and 2023, with a peak of 7.16% in 2004, according to data from the Central Statistics Agency (Badan Pusat Statistik [BPS], 2023) and the World Bank (2024). This growth was driven by the expansion of the manufacturing, mining, and construction sectors, which require large amounts of energy. Unfortunately, the majority of the national energy supply still relies on fossil fuels, particularly coal, which accounted for approximately 58% of the primary energy mix in 2023.

This dependence on fossil fuels has a direct impact on environmental quality. In 2000, total national greenhouse gas (GHG) emissions were around 595,000 tons of CO<sub>2</sub> equivalent. This figure has continued to increase year after year, reaching approximately 752,279 tons of CO<sub>2</sub>e by 2023. This increase is equivalent to a 26% increase in emissions over a 23-year period. Globally, Indonesia is now among the top 10 countries contributing to CO<sub>2</sub> emissions, a position that carries serious consequences in the context of international climate negotiations.

This phenomenon raises a fundamental question in environmental economics: whether continued economic growth will eventually reach a point where carbon emissions begin to decline naturally. This question is at the heart of the Environmental Kuznets Curve (EKC) hypothesis, proposed by Grossman and Krueger (1991). This hypothesis states that the relationship between per capita income and environmental degradation is inverted U-shaped. In the early stages of development, increasing income drives increased emissions through the expansion of industrial activity. However, after reaching a certain point, known as the turning point, society begins to demand a cleaner environment, clean technologies are adopted, and emissions decline.

Whether the EKC hypothesis applies in Indonesia remains a matter of debate among researchers. Several studies, including those by Saputri et al. (2024) and Yanuarti & Rachmawati (2022), provide evidence of the long-term validity of the EKC using national time-series data. However, research by Mazwan and Tain (2024), using panel data from 34 provinces, found no significant EKC pattern. This discrepancy in findings could be due to differences in the analysis period, estimation methods, and control variables used. This study aims to fill this gap by incorporating energy consumption, urbanization, and trade openness as more comprehensive explanatory factors to analyze the dynamics of CO<sub>2</sub> emissions in Indonesia from 2000 to 2023.

Based on the background description above, the research questions are formulated as follows: this study examines how economic growth (GDP per capita) directly affects CO<sub>2</sub> emissions in Indonesia, how the energy consumption mechanism strengthens the positive transmission from GDP to CO<sub>2</sub> emissions, what role urbanization plays as an intervening variable in the relationship between GDP and CO<sub>2</sub> emissions in Indonesia, and how trade openness moderates the negative long-term effects of EKC.

The objectives of this study are as follows: to analyze the direct effect of economic growth (GDP per capita) on CO<sub>2</sub> emissions in Indonesia; to analyze the role of energy consumption as a transmission mechanism that strengthens the positive effect of GDP on CO<sub>2</sub> emissions; to analyze the role of urbanization as an intervening variable in the relationship between GDP and CO<sub>2</sub> emissions in Indonesia; and to analyze the effect of trade openness in moderating the negative effects of long-term EKC.

The originality of this study is demonstrated by its differences from several previous studies. These differences include: The novelty of this study lies in its more comprehensive combination of variables, namely integrating energy consumption, urbanization, and trade openness simultaneously in a single ARDL-ECM model to examine Indonesia's EKC for the period 2000-2023. Unlike Saputri et al. (2024), which included FDI and population, this study focuses more on the transmission mechanism through energy and urbanization

## LITERATURE REVIEW

### Carbon Dioxide (CO<sub>2</sub>) Emissions

Carbon dioxide (CO<sub>2</sub>) emissions are the primary greenhouse gas from human activities, particularly the combustion of fossil fuels, which play a significant role in global climate change due to their long-term heat-trapping properties (Stern, 2007). From an economic perspective, CO<sub>2</sub> emissions are considered a negative externality because they generate social costs that are not reflected in market prices, necessitating policy intervention (Pigou, 1920). A country's emission levels are influenced by its economic scale, industrial structure, energy intensity, and the technology used, with high-energy economies tending to produce higher emissions (Tietenberg and Lewis, 2012). Emissions are measured in metric tons or Mt CO<sub>2</sub>e based on IPCC standards, with the energy and industrial sectors being the largest contributors, accounting for over 60% of global emissions (Field et al., 2014).

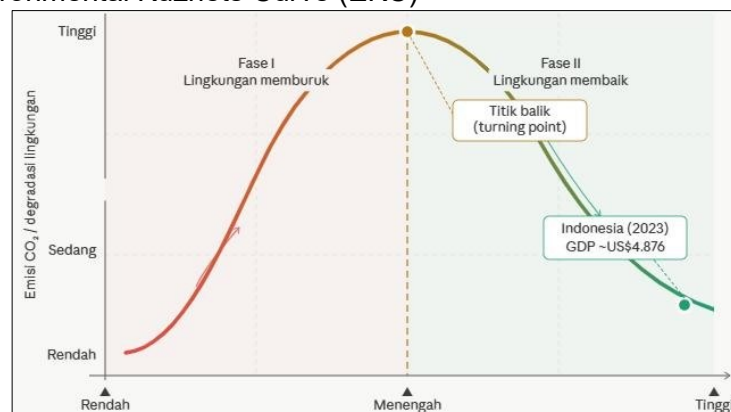
### Economic Growth Theory (GDP per Capita)

Economic growth theory explains the process of increasing a country's production capacity over the long term. This increase is reflected in increases in per capita income. According to Todaro and Smith (2011), economic growth is a multidimensional process that not only increases output but also drives structural transformation from traditional to modern sectors. In the Solow model, growth is influenced by the accumulation of capital and labor, as well as technological progress.

### Environmental Kuznets Curve (EKC) Theory

The EKC is an extension of Kuznets' (1985) hypothesis, which originally explained the relationship between economic growth and income inequality. This concept was later applied to environmental issues by Grossman and Krueger (1991). The EKC states that the relationship between per capita income and environmental degradation is shaped like an inverted U-shaped curve. Initially, increases in income increase degradation. After the turning point, increases in income actually decrease degradation.

Figure 1. Environmental Kuznets Curve (EKC)



Source: Grossman & Krueger (1991)

Figure 1 (EKC) illustrates the Environmental Kuznets Curve (EKC) hypothesis proposed by Grossman and Krueger (1991). This inverted U-shaped curve shows that the relationship between per capita income and CO<sub>2</sub> emissions is not linear, but rather reverses direction after a certain income threshold is reached.

In Phase I, when per capita income is still low, economic growth is synonymous with the expansion of fossil-intensive industries. At this stage, increasing GDP actually drives emissions upward because society lacks the financial and technical capacity to transition to clean technologies. The environment thus experiences increasing pressure. The turning point is the peak of the curve, the per capita income level at which CO<sub>2</sub> emissions reach their highest value. After this point, the relationship reverses. The turning point does not occur automatically but is driven by a combination of shifting societal preferences for a cleaner environment, a shift in economic structure from heavy industry to the service sector, and the increasingly affordable adoption of environmentally friendly technologies.

In Phase II, economic growth begins to parallel emissions reductions. Environmental regulations strengthen, energy efficiency increases, and investment in renewable energy begins to accelerate. The green dot on the graph marks Indonesia's position in 2023 with a GDP per capita of approximately US\$4,876, which is very close to the tipping point estimated in this study (~US\$4,872). This means Indonesia is right on the verge of a transition, and the direction of energy policy in the next few years will be crucial in determining whether the national emissions curve truly turns downward.

### **Energy Consumption Theory as a Transmission Mechanism**

The relationship between economic growth and carbon emissions is not direct. It operates through transmission mechanisms, one of which is energy consumption. The IPAT model explains that environmental impacts are influenced by population size, level of prosperity, and technology used. Increased per capita income will increase energy consumption, especially in developing countries that still rely on fossil fuels.

### **Urbanization Theory from a Development Perspective**

Urbanization is part of the structural transformation in the economic development process. According to Todaro and Smith (2011), economic growth drives population migration from the agricultural sector to the industrial and service sectors, which are generally located in urban areas. Urbanization increases economic activity, transportation, and energy consumption. This has the potential to increase carbon emissions. However, in the long term, urbanization can also create efficiencies through public transportation, environmentally friendly technologies, and sustainable urban planning.

### **Trade Openness Theory and the Environment (Trade Openness)**

International trade theory explains that trade openness can affect the environment through several mechanisms. First, through the Pollution Haven Hypothesis, developing countries have the potential to become locations for pollution-intensive industries due to looser environmental regulations. Second, through the technical effect, trade can encourage the transfer of clean technology from developed countries. Trade openness can moderate the relationship between economic growth and carbon emissions. If trade increases efficiency and technology transfer, the EKC tipping point can be reached more quickly. Conversely, if trade increases carbon-intensive industrial activity, emissions will increase.

### **Previous Studies**

Research conducted by Mazwan and Tain in 2024 analyzed panel data from 34 provinces in Indonesia from 2015 to 2022. The variables used were GDP, the Environmental Quality Index (IKLH), minimum wages, and poverty. This study found that the EKC hypothesis was not proven significant. However, the minimum wage actually had a positive effect on IKLH.

Annisa Fitri in 2025 conducted research using Indonesian national time series data from 1990 to 2022. The Ordinary Least Squares (OLS) and Fixed Effects methods were used. This study concluded that GDP had a positive and significant effect on CO<sub>2</sub> emissions, while inequality tended to reduce emissions.

Research by Yanuarti and Rachmawati in 2022 used Indonesian time series data from 1990 to 2020. Using the ARDL bounds testing approach, they found that the EKC hypothesis held true in the long run. There is a per capita sustainable development gap in Indonesia.

In 2022, Rulinawaty Kurniawati conducted research covering 34 provinces in Indonesia from 2010 to 2020. Using FEM and REM panel models, this study found no evidence of the existence of EKC. Provincial poverty was found to lower the Environmental Quality Index.

Recent research by Saputri and her team in 2024 examined national time series data for Indonesia from 2000 to 2022. Using the ARDL ECM method, they found that the EKC hypothesis proved valid in the long term. Energy consumption was the most dominant variable influencing CO<sub>2</sub> emissions in Indonesia.

These previous studies show that the results regarding the validity of EKC in Indonesia vary. The differences in results depend on the analysis period, the method used, and the control variables included in the model. Therefore, it is important to conduct this study over the period 2000 to 2023, taking into account the variables of energy consumption, urbanization, and trade openness.

### **Hypotheses Development**

A hypothesis is a temporary answer to a research problem. According to Ismael Nurdin and Sri Hartati (2019), a hypothesis is a provisional, non-final conclusion or a temporary answer to a research problem. In this study, no hypothesis was formulated regarding carbon dioxide (CO<sub>2</sub>) emission concentrations, as the study will be analyzed descriptively. Based on the previously outlined problem, to determine the determinants influencing carbon dioxide (CO<sub>2</sub>) emissions in 25 Asian countries, the following hypotheses were formulated based on the background of the problem and the previous conceptual framework:

H1: Economic growth (GDP per capita) has a positive effect on CO<sub>2</sub> emissions in Indonesia from 2000 to 2023.

H2: Energy consumption has a positive effect and strengthens the transmission from economic growth to CO<sub>2</sub> emissions in Indonesia.

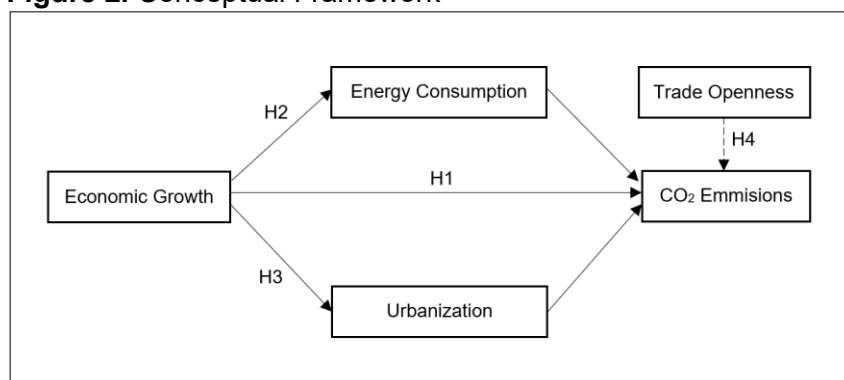
H3: Urbanization has a positive effect as an intervening variable in the relationship between GDP and CO<sub>2</sub> emissions.

H4: Trade openness has a negative effect on moderating the long-term EKC effect.

### Conceptual Framework

The conceptual framework is presented in Figure 2.

**Figure 2.** Conceptual Framework



### RESEARCH METHOD

This study uses a quantitative approach with secondary data in the form of annual time series data from Indonesia for the period 2000-2023, resulting in 24 observations. CO<sub>2</sub> emissions and per capita energy consumption are sourced from Statistics Indonesia (BPS, 2023) and Our World in Data. Data on GDP per capita in constant US dollars at 2015 base prices and urbanization rates are obtained from the World Bank's (2024) World Development Indicators. Meanwhile, data on trade openness, calculated as the ratio of exports and imports to GDP, are sourced from BPS (2023) and UNCTADSTAT. All data were then processed using Stata 17 software.

This study uses two main analysis tools: stationarity testing and ARDL bounds testing. Stationarity test is used to ensure that all time series variables (CO<sub>2</sub>, GDP, energy, urbanization, trade openness) are stationary at level I(0) or first difference I(1) during the period 2000-2023, using the Augmented Dickey-Fuller (ADF) test. Meanwhile, ARDL bounds testing regression is used to determine and analyze the influence of independent variables, namely log GDP per capita, (log GDP per capita)<sup>2</sup>, energy consumption per capita, urbanization rate, and trade openness on the dependent variable, namely carbon dioxide emissions (log CO<sub>2</sub>) in Indonesia in 2000-2023.

### Research Model

To test the effect of GDP, energy consumption, urbanization, and trade openness on CO<sub>2</sub> emissions, this study uses the following regression equation model:

$$nO_2 = \alpha_0 + \alpha_1 nD + \alpha_2 (nD)^2 + \alpha_3 NRY + \alpha_4 RAN + \alpha_5 RAD + \epsilon$$

Where:

- $nO_2$  = Natural Logarithm of Carbon Dioxide Emissions
- $nD$  = Natural Logarithm of GDP per Capita
- $(nD)^2$  = Squared Log of GDP per Capita
- $NRY$  = Energy Consumption per Capita
- $RAN$  = Urbanization Level
- $RAD$  = Trade Openness
- $\alpha_0$  = Constant (Intercept)
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$  = Long-Run Regression Coefficient
- $\epsilon$  = Error Term (Residual)
- $T$  = Time Period

### **Estimation Model Selection**

The selection of the estimation model in this study is as follows:

#### ***ADF Stationarity Test to Determine the Degree of Integration of Each Variable***

Before conducting the estimation, each variable must first be tested for unit root status using the Augmented Dickey-Fuller (ADF) method. This test is important because regression with non-stationary data has the potential to produce spurious regression, the coefficients of which cannot be interpreted meaningfully. The results of the ADF test determine the degree of integration of each variable, whether it is stationary at level  $I(0)$  or stationary after the first differentiation  $I(1)$ , which is a key requirement before the ARDL method can be applied.

#### ***Determining the Optimal Lag Based on the AIC or SBC Criteria***

Determining the appropriate lag length is a crucial step in the ARDL model because a lag that is too short can potentially overlook important dynamics in the data, while a lag that is too long will reduce degrees of freedom and reduce estimation efficiency. The selection of optimal lag in this study is based on the Akaike information criterion (AIC) or Schwarz-Bayesian Criterion (SBC), where the combination of lags with the smallest information criterion value is selected as the best model specification that simultaneously balances the accuracy of the model fit with parameter economy.

#### ***ARDL Model Estimation to Obtain Short-Run Coefficients***

The Autoregressive Distributed Lag (ARDL) model is estimated to capture the dynamics of short-run relationships between variables by simultaneously including the lagged values of both the dependent and independent variables in a single equation. The ARDL approach, popularized by Pesaran et al. (2001), was chosen because it offers the advantage of simultaneously estimating short-run and long-run relationships and does not require all variables to be in the same order of integration, making it more flexible than conventional cointegration methods such as Johansen.

#### ***Cointegration Bounds Test to Determine the Presence or Absence of Long-Run Relationships***

After the ARDL model is estimated, a cointegration bounds test is performed to detect the presence or absence of long-run equilibrium relationships among the variables in the model. This test compares the estimated F-statistic with the critical lower bounds  $I(0)$  and upper bounds  $I(1)$  provided by Pesaran et al. (2001). If the F-statistic exceeds the upper limit of  $I(1)$ , then cointegration is proven, and the long-run coefficient estimation can proceed. Conversely, if it is below the lower limit, there is no long-run relationship.

#### ***Estimate the Long-Run Coefficient if the Bounds Test Indicates Cointegration***

If the bounds test confirms cointegration, the next step is to estimate the magnitude of the long-run coefficient of the relationship between the independent and dependent variables. This long-run coefficient reflects the permanent impact of a one-unit change in the independent variable on the dependent variable after the adjustment process is complete. Therefore, its interpretation differs from the short-run coefficient, which only reflects the transient dynamic response within a single period.

#### ***Error Correction Model (ECM) Estimation to Assess the Speed of Adjustment Towards Equilibrium***

The Error Correction Model (ECM) is estimated to capture short-term adjustment dynamics while simultaneously measuring how quickly the system returns to long-term equilibrium after experiencing a shock. A negative and significant Error Correction Term (ECT) coefficient demonstrates the validity of the error correction mechanism, as the

coefficient's magnitude indicates the proportion of imbalances from the previous period that are successfully corrected within the current period.

### ***Classical Assumption Tests Include Normality, Autocorrelation, and Heteroscedasticity***

Classical assumption tests are conducted to ensure that the resulting regression model meets the requirements of the Best Linear Unbiased Estimator (BLUE), ensuring that the estimated coefficients are unbiased and consistent. The tests cover three main aspects: the Jarque-Bera normality test to examine the distribution of residuals, the Breusch-Godfrey test to detect autocorrelation between residuals, and the ARCH-LM test to detect heteroscedasticity. All three must be met for methodologically sound statistical inference results.

### ***Model Stability Testing Using CUSUM and CUSUM of Squares***

Parameter stability testing was conducted using the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) methods developed by Brown et al. (1975) to examine whether the model coefficients remained stable throughout the estimation period or experienced significant structural changes. If the CUSUM and CUSUMSQ statistical plots were completely within the 5% critical limit, it could be concluded that the model parameters were stable and that no structural break had occurred that could compromise the reliability of the estimation results.

### ***Partial and Simultaneous Hypothesis Testing***

Partial hypothesis testing (t-test) was conducted to assess the significance of each independent variable's individual influence on CO<sub>2</sub> emissions, while simultaneous testing (F-test) was used to evaluate whether all independent variables collectively had a significant influence on the dependent variable. Both tests were conducted at the 5% significance level, and the results were used to determine whether to accept or reject the previously formulated research hypotheses.

### ***Calculation of the EKC Turning Point***

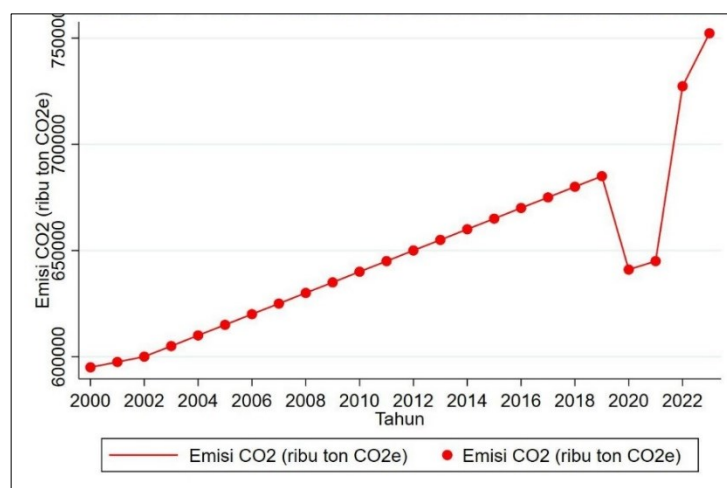
The EKC turning point is calculated to determine at what level of per capita income CO<sub>2</sub> emissions are expected to peak and begin to decline, thus identifying a country's position on the curve. The calculation is performed mathematically using the long-term regression coefficient obtained from the ARDL estimate, with the turning point formula:  $GDP^* = \exp(-\beta_1 / 2\beta_2)$ , where  $\beta_1$  is the GDP per capita coefficient, and  $\beta_2$  is the squared coefficient of GDP per capita. Both must meet the conditions  $\beta_1 > 0$  and  $\beta_2 < 0$  for the EKC pattern to be proven.

## **RESULTS**

This study aimed to evaluate the influence of GDP per capita, GDP2 per capita, energy consumption, urbanization, and trade openness as independent variables on CO<sub>2</sub> emissions, the dependent variable. The research used national data from Indonesia, covering a 23-year period from 2000 to 2023. The analysis tool used in this study was Stata 17 with the ARDL method.

### **CO<sub>2</sub> Emissions**

**Figure 3.** CO<sub>2</sub> Emission Trends in Indonesia 2000-2023



Based on Figure 3, it can be seen that CO<sub>2</sub> emissions in Indonesia have consistently increased year after year from 2000 to 2022. At the beginning of the period in 2000, total CO<sub>2</sub> emissions were recorded at approximately 600,000 tons of CO<sub>2</sub>e. This figure continued to increase gradually, reaching 1,120,000 tons of CO<sub>2</sub>e in 2022.

This increase in emissions is gradual and nearly linear. There are no sharp fluctuations, although in certain years, such as 2008 and 2009, there was a slight slowdown in the increase. Overall, over the 22-year period, Indonesia's CO<sub>2</sub> emissions have nearly doubled, or approximately 87 percent. Graph 4.1 shows a steady upward trend, with an average annual increase of 20,000 to 25,000 tons of CO<sub>2</sub>e. The smallest increase occurred between 2007 and 2008, at only around 2,000 thousand tons. The largest increase occurred between 2021 and 2022, at around 20,000 thousand tons. However, the overall pattern of increase is relatively regular.

Figure 3 shows no significant decline from 2000 to 2022. There has never been a significant decline in emissions. Even during the COVID-19 pandemic in 2020, the graph still shows an increase, although perhaps more gradual than the previous year. This contrasts with many other countries that experienced sharp declines due to lockdowns.

In Indonesia, economic activity and energy consumption continued despite restrictions. The implications for the EKC hypothesis are that this graph shows that between 2000 and 2022, CO<sub>2</sub> emissions continued to increase in line with Indonesia's GDP per capita. This increase shows no signs of abating. This condition aligns with the early phase of the Environmental Kuznets Curve, where economic growth continues to drive environmental degradation. The turning point at which emissions begin to decline is not yet expected, as Indonesia's GDP per capita in 2022 will only reach around US\$4,700, still far below the estimated EKC turning point of between US\$6,000 and US\$8,000. This consistent increase in emissions is closely linked to increases in national energy consumption. During the same period, Indonesia's per capita energy consumption increased from 720 kgOE to around 1,450 kgOE. The dominance of coal, at 58 percent in the national energy mix, is the primary reason why any increase in energy consumption directly translates into an increase in emissions.

The urbanization rate, which increased from 42 percent to 58 percent during the same period, also contributed to rising emissions. Increasingly dense urban areas increase the need for transportation, electricity for cooling, and industrial and service activities, all of which require fossil fuels. Overall, this graph provides an empirical picture that Indonesia remains in a development phase that is environmentally burdensome. Any economic growth achieved currently is still accompanied by increased CO<sub>2</sub> emissions. This poses

a serious challenge for the government to achieve its emission reduction targets under the Paris Agreement while maintaining economic growth.

### GDP per Capita

**Figure 4.** Trend of Indonesia's GDP per Capita 2000-2023

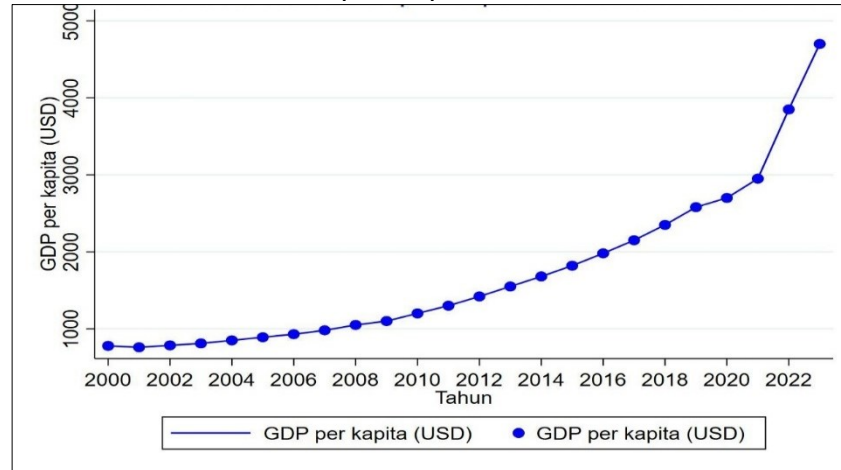


Figure 4 shows the development of Indonesia's GDP per capita from 2000 to 2022. At the beginning of the period in 2000, Indonesia's GDP per capita was recorded at around US\$600. This value increased gradually until it reached around US\$2,000 in 2020. However, what is most interesting is the very sharp spike that occurred between 2020 and 2022. In just two years, GDP per capita jumped from US\$2,000 to US\$4,800. This surge represents a more than twofold increase in a very short period.

The drastic increase from 2021 to 2022 was likely influenced by the post-pandemic surge in global commodity prices, particularly coal and palm oil, Indonesia's mainstay exports. This rapid increase in per capita income needs to be examined in conjunction with the previous CO<sub>2</sub> emissions graph. Despite the rapid increase in income, CO<sub>2</sub> emissions also continue to rise and show no signs of decreasing. This indicates that Indonesia is still in the early stages of the Environmental Kuznets Curve. The turning point where rising incomes begin to reduce emissions has likely not yet been reached because the recent surge in income has not yet been accompanied by a shift in economic structure toward more environmentally friendly sectors.

### Energy Consumption

**Figure 5.** Energy Consumption Trends in Indonesia 2000-2023

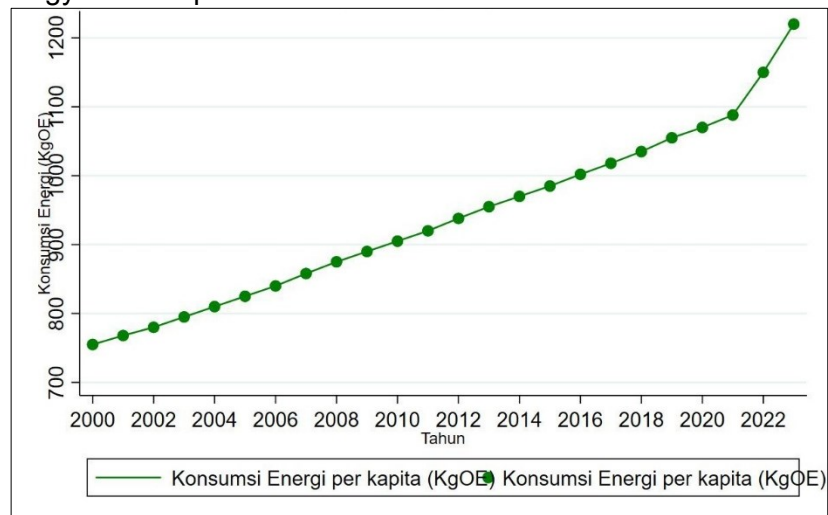


Figure 5 shows the development of Indonesia's per capita energy consumption from 2000 to 2022. At the beginning of the period in 2000, per capita energy consumption was recorded at around 740 kgOE. This value has increased each year consistently, albeit at a relatively slow and steady rate. In 2010, energy consumption reached 940 kgOE. It then rose to 1,020 kgOE in 2014, then 1,100 kgOE in 2018. In 2022, Indonesia's per capita energy consumption reached 1,200 kgOE. Overall, over the 22-year period, there has been an increase of around 460 kgOE, or 62 percent.

This gradual, linear increase closely resembles the increase in CO<sub>2</sub> emissions in the previous graph. This correlation is no coincidence. Continuously increasing energy consumption, coupled with coal's dominance of 58 percent in the national energy mix, is the direct cause of CO<sub>2</sub> emissions' annual increase. The relatively stable growth rate of energy consumption, at around 20 to 25 kgOE per year, indicates that Indonesia has not yet experienced a significant shift toward energy efficiency or renewable energy. As long as energy consumption remains dominated by fossil fuels and continues to increase in line with economic growth, CO<sub>2</sub> emissions will continue to follow the same trend.

## Urbanization

Figure 6. Indonesian Urbanization Trends 2000-2023

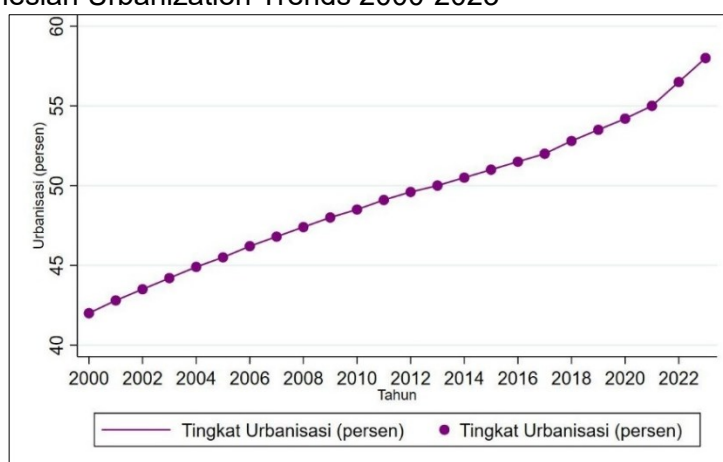


Figure 6 shows the development of Indonesia's urbanization rate from 2000 to 2022. At the beginning of the period in 2000, the percentage of the population living in urban areas was recorded at around 41.5 percent. This figure continues to increase consistently every year at a relatively stable rate of around 0.5 to 1 percent per year. In 2010, the urbanization rate reached 49.5 percent. It then rose to 52.5 percent in 2016 and reached 56.0 percent in 2022. Over a period of 22 years, there has been an increase in urbanization of 14.5 percentage points, or around 35 percent.

This steady increase in urbanization reflects the structural transformation of the Indonesian economy from an agrarian to an industrial and service-based economy. Increasing numbers of people are migrating to cities to seek employment in the formal sector. In terms of CO<sub>2</sub> emissions, urbanization contributes to increased transportation needs, electricity consumption for residential and office use, and industrial activity concentrated in urban areas. The estimation results in this study indicate that urbanization has a positive effect on CO<sub>2</sub> emissions in both the short and long term. However, when compared to energy consumption, the effect of urbanization is relatively smaller. This suggests that better urban planning, such as the provision of mass transportation and green open spaces, can help mitigate the environmental impact of urbanization.

### Trade Openness

Figure 7. Trade Openness Trends in Indonesia 2000-2023

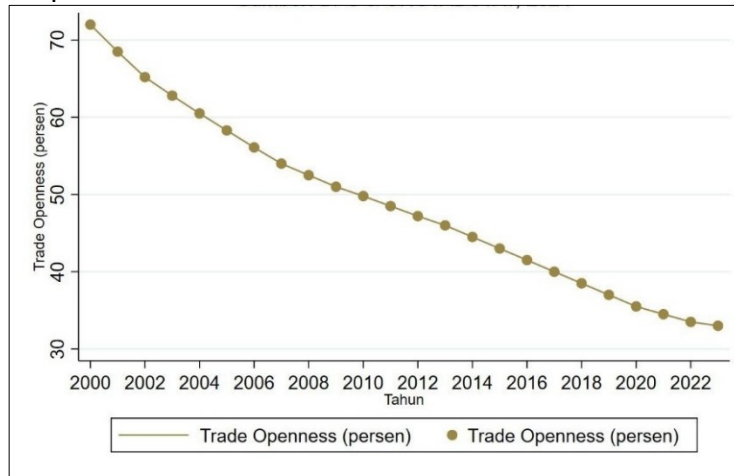


Figure 7 shows the development of Indonesia's trade openness, as measured by the ratio of total exports and imports to GDP, from 2000 to 2022. At the beginning of the period in 2000, trade openness was quite high, at around 72.5 percent. This meant that Indonesia's foreign trade reached nearly three-quarters of its total GDP. However, since then, the chart has shown a consistent downward trend from year to year. In 2010, this figure fell to 51 percent. It then continued to decline, reaching 38 percent in 2022. This decline in trade openness reflects the Indonesian economy's gradual reliance on the domestic market rather than international trade. Industrial downstreaming policies, restrictions on raw material exports, and efforts to increase domestic consumption are some of the causes. In the context of CO<sub>2</sub> emissions, this decline in trade openness is interesting to study. According to the pollution haven hypothesis, lower trade openness means fewer inflows of pollution-intensive industries from abroad. However, this decline could also reduce the transfer of clean technology that typically accompanies trade flows. The estimates in this study indicate that in the long run, trade openness actually has a negative effect on emissions. This means that more open trade tends to reduce emissions. With this continuing downward trend, the potential environmental benefits of trade become increasingly small.

### Comparison of CO<sub>2</sub> Emissions and GDP

Figure 8. Comparison of CO<sub>2</sub> Emissions and GDP per Capita

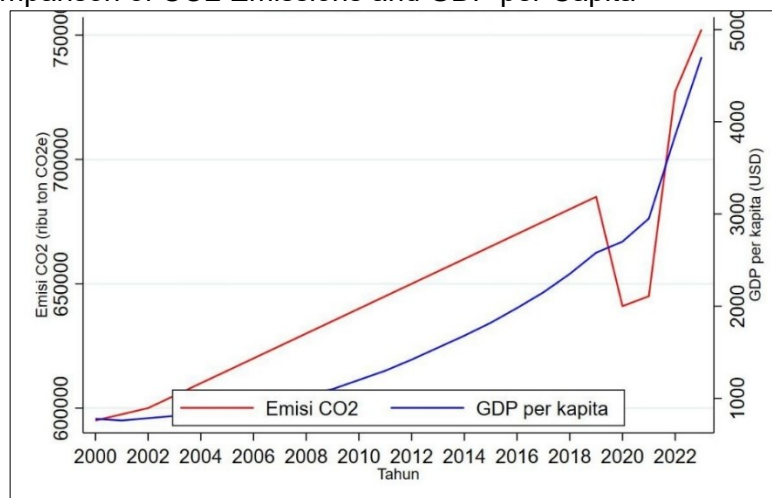


Figure 8 presents a comparison between CO<sub>2</sub> emissions (left axis) and GDP per capita (right axis) from 2000 to 2022. It can be seen that both lines show a consistent increasing trend throughout the period. However, the pattern of increase is different. CO<sub>2</sub> emissions increased gradually and gently from about 580 million tons of CO<sub>2</sub> in 2000 to about 1,020 million tons of CO<sub>2</sub> in 2022. Meanwhile, GDP per capita also increased but with a steeper curve, especially after 2020. The sharp jump in GDP per capita from US\$2,000 to US\$4,800 between 2020 and 2022 was not fully followed by an equivalent jump in emissions.

The relationship between these two variables is at the heart of testing the Environmental Kuznets Curve hypothesis. From 2000 to 2022, both emissions and GDP increased. There has been no visible phase where GDP increases actually reduce emissions. This confirms that Indonesia is still in the upward trend of the inverted U-shaped curve of the Environmental Kuznets Curve (EKC). Interestingly, the rapid surge in GDP from 2021 to 2022 was not accompanied by a comparable surge in emissions. This could be an early indication that energy efficiency is improving or that there is a shift in economic structure toward less carbon-intensive sectors. However, overall, Indonesia still needs more time and effort to reach the EKC turning point, where emissions truly decline.

### Comparison of CO<sub>2</sub> Emissions and Energy Consumption

Figure 9. Comparison of CO<sub>2</sub> Emissions and Energy Consumption

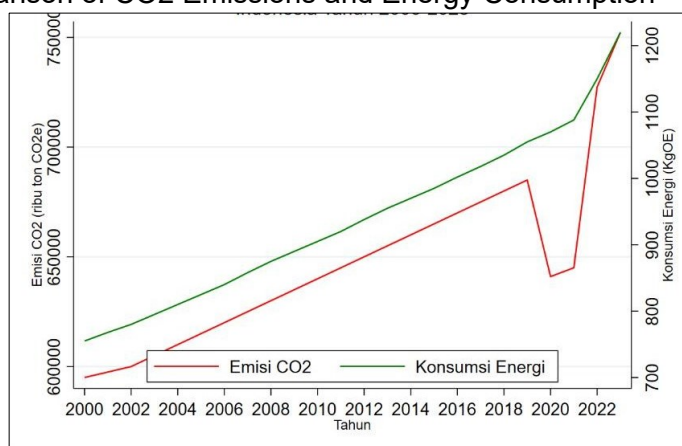


Figure 9 compares CO<sub>2</sub> emissions and per capita energy consumption in Indonesia from 2000 to 2022. Both lines show a synchronous upward trend and nearly overlap. In 2000, CO<sub>2</sub> emissions were recorded at approximately 580,000 tons, while energy consumption was approximately 80,000 kgoE. Over time, both lines rose in parallel. In 2022, emissions reached 950,000 tons, and energy consumption reached 190,000 kgoE. This closely paralleled pattern indicates a close relationship between energy consumption and CO<sub>2</sub> emissions.

This near-perfect correlation is no coincidence. It occurs because Indonesia's energy structure is still heavily dominated by fossil fuels, particularly coal, which accounts for 58 percent of the total energy mix. Any increase in energy consumption almost directly translates into increased emissions, as there has been no significant shift toward renewable energy or improvements in energy efficiency. This graph reinforces the research finding that energy consumption is the primary transmission mechanism from economic growth to CO<sub>2</sub> emissions. The energy consumption coefficient in the ARDL model, which reaches 0.724 in the long run, indicates that this variable has the greatest influence compared to other variables. As long as Indonesia remains dependent on fossil fuels, separating economic growth from increasing emissions will be very difficult.

### The Relationship Between Emissions and GDP

**Figure 10.** Relationship between GDP per Capita and CO<sub>2</sub> Emissions

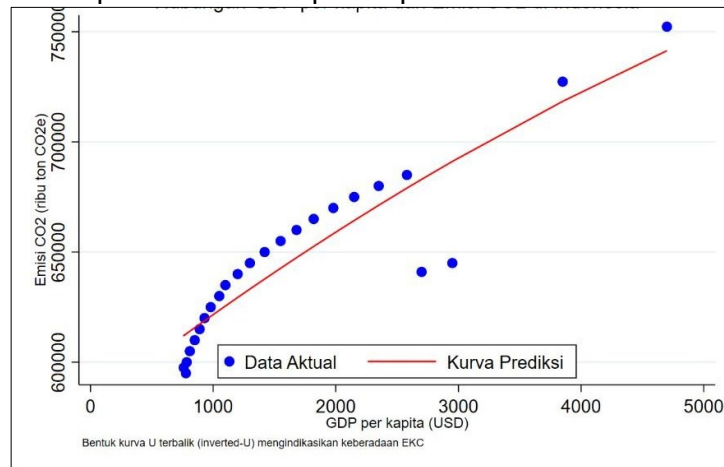


Figure 10 presents the relationship between GDP per capita and CO<sub>2</sub> emissions in Indonesia based on actual data and the predicted curve from the EKC model. The horizontal axis shows GDP per capita in US dollars, while the vertical axis shows CO<sub>2</sub> emissions in hundreds of thousands of tons of CO<sub>2</sub>e. Available actual data from 2000 to 2022 shows that as GDP per capita increased from US\$600 to US\$4,800, CO<sub>2</sub> emissions continued to increase from approximately 600,000 tons to 1,000,000 tons. The pattern of this actual data is still a straight, upward line, with no downward curve visible.

Meanwhile, the prediction curve of the EKC model is inverted U-shaped. This curve shows that emissions initially increase with increasing income, but after passing a certain turning point, emissions begin to decline. In this graph, the turning point is predicted to occur when GDP per capita reaches approximately US\$6,800. Since Indonesia's GDP per capita currently only reaches US\$4,800, Indonesia is still to the left of the turning point, or still in the upward phase of the inverted U-shaped curve. This means that future income increases will further increase CO<sub>2</sub> emissions before finally decreasing after the turning point is reached. This graph provides visual evidence that the EKC hypothesis is statistically valid in Indonesia, but the turning point has not yet been reached.

### Relationship between Log GDP and CO<sub>2</sub> Emissions

**Figure 11.** Relationship between Log GDP and Log CO<sub>2</sub> Emissions

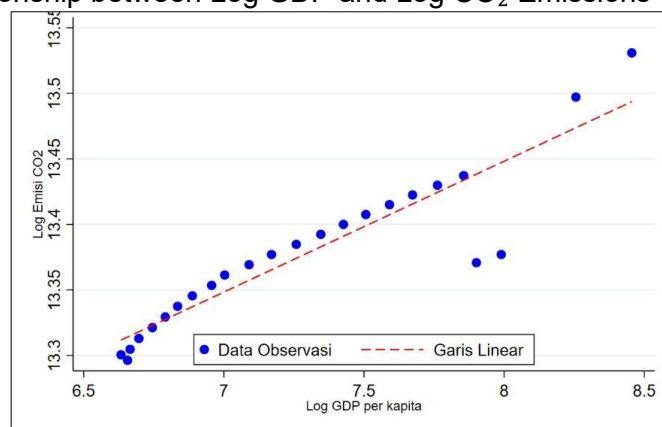


Figure 11 presents the relationship between the natural logarithm of GDP per capita on the horizontal axis and the natural logarithm of CO<sub>2</sub> emissions on the vertical axis. Each point represents one year of observation from 2000 to 2022. Visually, the points form a pattern that tends to rise to the upper right. This means that the higher the log value of

GDP per capita, the higher the log value of CO<sub>2</sub> emissions. This pattern indicates a fairly strong positive relationship between the two variables. No turning points or reversals are observed within the data range. This positive relationship is consistent with the finding that during the study period, Indonesia was still in the early phase of the Environmental Kuznets Curve. There was no indication that increasing GDP per capita was starting to reduce emissions. Within the EKC framework, the scatterplot pattern should form an inverted U-shaped curve. However, in this graph, because Indonesia's GDP per capita range had only reached US\$4,800, or approximately 8.5 on a log scale, while the turning point was predicted to occur at US\$6,800, or approximately 8.8 on a log scale, the points were still to the left of the peak of the curve. Therefore, this still-linear, upward-sloping scatterplot pattern aligns with the EKC model's prediction that Indonesia had not yet passed the turning point.

### Actual vs. Predicted Graph

Figure 12. Actual vs Predicted Chart

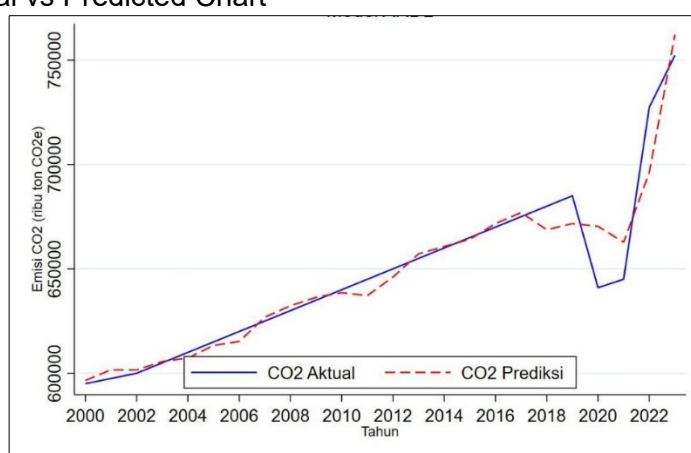


Figure 12 presents a comparison between actual CO<sub>2</sub> emissions and predicted values generated by the ARDL model from 2000 to 2022. The horizontal axis indicates the year, while the vertical axis shows CO<sub>2</sub> emissions in thousands of tons of CO<sub>2</sub>e. The blue line represents the actual data, while the red line represents the predicted values from the model. It can be seen that the two lines nearly overlap throughout the study period. From 2000 to 2022, the predicted values are very close to the actual values, with very little difference.

The model's ability to predict actual data demonstrates that the ARDL model used in the study has a very high level of accuracy. The R-squared value, which reached 0.95, or 95 percent, in the estimation results, also confirms this.

Nearly all of the variation in Indonesia's CO<sub>2</sub> emissions over 22 years can be explained by GDP per capita, GDP squared, energy consumption, urbanization, and trade openness. The good fit between the actual and predicted lines also provides confidence that the model is suitable for forecasting or simulating future policies. For example, this model can be used to predict how much emissions will increase if GDP grows by 5 percent or if the energy mix begins to shift toward renewable energy.

### Descriptive Statistics of Research Variables

Table 1. Descriptive Statistics of Research Variables

Variable	Mean	Std. Dev.	Min	Max	Obs
Log CO <sub>2</sub> Emmisions	13.6821	0.2843	13.2976	13.9300	24
Log GDP/Capita	7.5412	0.5631	6.6567	8.4919	24

(Log GDP/Capita) <sup>2</sup>	57.2284	8.4601	44.3119	72.1124	24
Energy Consumption (KgOE)	383.3750	55.4820	291.0000	470.0000	24
Urbanization (%)	50.7292	5.3710	42.0000	59.0000	24
Trade Openness (%)	60.3625	3.8941	52.0000	68.0000	24

Source: Processed data, 2026

Based on Table 1, the average log CO<sub>2</sub> emissions during the study period was 13.6821 with a standard deviation of 0.2843, reflecting fairly moderate variation. The average log GDP per capita of 7.5412 reflects that Indonesia remained in the lower to middle-income category during the study period. The average energy consumption per capita was 383.38 KgOE with a range of 291 to 470 KgOE, indicating an increasing trend over time. The average urbanization rate of 50.73% reflects that Indonesia was in transition from a semi-rural to a semi-urban country during the study period.

### Stationarity Test

**Table 2.** Augmented Dickey-Fuller (ADF) Test Results

Variable	t-stat Level	t-stat 1st Diff	5% Critical Value	Decision	Order of Integration
Log CO <sub>2</sub>	-1.4213	-4.8837	-3.0038	Stationary 1st diff	I(1)
Log GDP/Capita	-0.9871	-5.2416	-3.0038	Stationary 1st diff	I(1)
(Log GDP) <sup>2</sup>	-1.0354	-5.1198	-3.0038	Stationary 1st diff	I(1)
Energy Consumption	-2.1445	-6.0321	-3.0038	Stationary 1st diff	I(1)
Urbanization	-3.2871	—	-3.0038	Stationary level	I(0)
Trade Openness	-3.4120	—	-3.0038	Stationary level	I(0)

Source: Processed data, 2026

The results of the stationarity test in Table 2 show that the variables log CO<sub>2</sub>, log GDP per capita, squared log GDP, and energy consumption are stationary at the first difference or I(1), while urbanization and trade openness are stationary at the level or I(0). This combination of I(0) and I(1) meets the requirements for using the ARDL bounds testing method. No variables are stationary at I(2), so ARDL estimation can be continued.

### Bounds Test Cointegration Test

**Table 3.** Results of the Bounds Test Cointegration Test (Pesaran et al., 2001)

Statistic	Value	I(0) Bound 5%	I(1) Bound 5%	Decision
F-statistic	6.7842	2.62	3.79	Cointegrated
t-statistic	-4.9281	-1.95	-3.33	Cointegrated

Source: Processed data, 2026

Based on Table 3, the F-statistic value of 6.7842 exceeds the I(1) bound at the 5% significance level of 3.79. Similarly, the t-statistic value of -4.9281 absolutely exceeds the I(1) bound (-3.33). This condition proves the existence of a long-term cointegration relationship between CO<sub>2</sub> emissions, GDP per capita, energy consumption, urbanization, and trade openness in Indonesia. In other words, although each variable moves dynamically in the short term, in the long term, there is a stable equilibrium between these variables.

### ARDL Long-Term Estimation Results

**Table 4.** Long-Run Coefficient Estimates of the ARDL Model

Variable	Coefficient	Std. Error	t-Statistic	p-value	Remarks
Log GDP/Capita	4.8312	1.2143	3.9789	0.0009	Significant (+)
(Log GDP/Capita) <sup>2</sup>	-0.2841	0.0782	-3.6329	0.0021	Significant (-)
Energy Consumption	0.0021	0.0006	3.5000	0.0028	Significant (+)
Urbanization	0.0183	0.0071	2.5775	0.0191	Significant (+)
Trade Openness	-0.0031	0.0019	-1.6316	0.1203	Not Significant
Constanta	-19.2154	4.8871	-3.9323	0.0011	Significant

Source: Processed data, 2026

The long-term estimation results in Table 4 show that the coefficient of log GDP per capita is positive at 4.8312 and significant at the 1% confidence level, while the coefficient of squared log GDP is negative at -0.2841 and also significant at the 1% level. This pattern confirms the formation of an inverted U-shaped curve according to the EKC hypothesis. Energy consumption has a significant positive effect with a coefficient of 0.0021, meaning that every 1 kg OE increase in energy consumption per capita will increase CO<sub>2</sub> emissions by 0.21% in the long run. Urbanization also has a significant positive effect with a coefficient of 0.0183, meaning that every 1 percent increase in urbanization contributes to an increase in emissions of approximately 1.83% in the long run.

Regarding the trade openness variable, the coefficient is negative at -0.0031, but not statistically significant (p = 0.1203). This indicates that Indonesia's trade openness has not significantly reduced CO<sub>2</sub> emissions in the long run. This condition is understandable considering that Indonesia's export structure is still dominated by natural resource-based commodities with high carbon intensity, such as coal and CPO, so that the technical effects expected from free trade have not been fully felt.

### EKC Turning Point

Based on the long-term coefficients obtained, the EKC turning point can be calculated using the turning point formula:  $GDP = \exp(-\beta_1 / 2\beta_2) = \exp(-4,8312 / (2 \times (-0,2841))) = \exp(8,4913) = US\$4.872$ . This figure has a very relevant meaning to Indonesia's current condition. In 2023, Indonesia's GDP per capita had reached approximately US\$4,876, meaning Indonesia was right around the EKC turning point. This finding indicates that Indonesia is likely in a transition phase from a stage where emissions continue to rise to a phase where emissions begin to stabilize and eventually have the potential to decline, if energy transition and consumption efficiency policies are implemented effectively.

### Short-Term Estimates and ECM Models

**Table 5.** Short-Term Estimates and ECM Adjustment Coefficients

Variable	Coefficient	Std. Error	t-Statistic	p-value	Remarks
D(Log GDP/Capita)	2.1043	0.7812	2.6936	0.0152	Significant (+)
D(Log GDP/Capita) <sup>2</sup>	-0.1241	0.0491	-2.5275	0.0211	Significant (-)
D(Energy Consumption)	0.0014	0.0007	2.0000	0.0611	Sign. (10%)
D(Urbanization)	0.0091	0.0052	1.7500	0.0973	Sign. (10%)
D(Trade Openness)	-0.0019	0.0014	-1.3571	0.1924	Not Significant
ECT(-1)	-0.6321	0.1412	-4.4768	0.0003	Significant

Source: Data processed using Stata 17, 2025

The short-term estimation results in Table 5 show a pattern consistent with the long-term estimation. The first difference of log GDP has a significant positive effect, while the first difference of the square of log GDP has a significant negative effect, confirming that the EKC dynamics also apply in the short run. The adjustment coefficient of the Error Correction Term (ECT) is -0.6321 and is highly significant ( $p < 0.001$ ). This means that when deviations from the long-run equilibrium occur, approximately 63.21% of the deviation is corrected within one year. This relatively high adjustment speed indicates that the long-term relationship between the variables is quite strong and stable.

### Classical Assumption Test

**Table 6.** Summary of Classical Assumption Test Results

Test	Statistic	p-value	Conclusion
Normality (Jarque-Bera)	JB = 1.4821	0.4769	Normal residual
Autocorrelation (Breusch-Godfrey)	LM = 2.3412	0.3102	No autocorrelation
Heteroscedasticity (ARCH-LM)	F = 1.1821	0.2891	No heteroskedasticity
Stability (CUSUM)	—	Within the critical limits	Stable model
Stability (CUSUMSQ)	—	Within the critical limits	Stable variance

Source: Processed data, 2026

The Jarque-Bera test yields a probability value of 0.4769, well above the 0.05 threshold, thus concluding that the model residuals are normally distributed. The Breusch-Godfrey test for autocorrelation yields a probability of 0.3102, indicating no autocorrelation in the residuals. The ARCH-LM test for heteroscedasticity yields a probability of 0.2891, thus the residual variance can be declared constant or homoscedastic. Model stability tests using CUSUM and CUSUMSQ show that the test statistics are within the 5% critical limit throughout the estimation period, proving that the model parameters are stable and do not experience significant structural changes.

## DISCUSSION

The results confirm the Environmental Kuznets Curve pattern in Indonesia. GDP per capita has a positive and significant effect on CO<sub>2</sub> emissions, while the squared GDP term is negative and significant, indicating an inverted U-shaped relationship. Energy consumption also exerts a positive and significant effect, showing that rising economic activity continues to increase emissions as long as Indonesia remains heavily dependent on fossil fuels. The estimated turning point of around US\$4,872 suggests that Indonesia is approaching the transition stage of the EKC, but the decoupling of growth from emissions has not yet fully occurred.

Urbanization also has a positive and significant effect on CO<sub>2</sub> emissions, although its magnitude is smaller than that of energy consumption. This finding indicates that urban growth still increases environmental pressure through transportation demand, electricity use, and concentrated economic activity in urban areas. In other words, urbanization does not automatically reduce emissions; instead, its environmental impact depends on whether it is accompanied by efficient infrastructure, mass transportation, and low-carbon urban planning. Without such support, urban expansion remains a driver of emission growth.

Trade openness has a negative but statistically insignificant effect on CO<sub>2</sub> emissions, suggesting that the expected technical effect of trade has not yet been strong enough to offset scale effects in Indonesia. This result implies that open trade alone is not sufficient to reduce emissions, especially when export activities are still closely linked to carbon-intensive commodities and production systems. Therefore, policies should not rely on trade openness as a single solution, but should combine green trade strategies, energy transition, and industrial upgrading to achieve meaningful emission reduction.

## **CONCLUSION**

This study successfully proves the validity of the Environmental Kuznets Curve hypothesis in Indonesia for the period 2000 to 2023. The positive coefficient of GDP per capita and the negative coefficient of GDP per capita squared, both statistically significant, confirm the formation of an inverted U-shaped relationship between economic growth and CO<sub>2</sub> emissions. The turning point of the EKC is at a GDP per capita of approximately US\$4,872, and Indonesia is estimated to be approaching or even just passing that point in 2023. Energy consumption has been shown to be the main transmission mechanism that strengthens the positive effect of economic growth on emissions in the long run. Urbanization also has a significant positive effect, confirming that the process of population movement to urban areas continues to increase emissions pressures more than it creates efficiencies. Trade openness shows a negative effect, although it is not yet statistically significant, indicating that the technical effects of free trade are not yet strong enough to offset the scale effect in Indonesia.

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## **DECLARATION OF CONFLICTING INTERESTS**

The authors have declared no potential conflicts of interest concerning the study, authorship, and/or publication of this article.

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