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Coal Consumption Dynamics in Indonesia: Evidence from the Coal Kuznets Curve (CKC) Framework

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Abstract

Background: Indonesia, as one of the world's largest coal producers and consumers, faces a critical tension between coal-driven economic growth and the imperative of environmental sustainability. Despite existing studies on the Environmental Kuznets Curve (EKC), empirical evidence on the Coal Kuznets Curve (CKC) in Indonesia remains limited, particularly regarding the nonlinear dynamics of coal consumption over time.
Objective: This study analyzes the influence of economic growth on coal consumption in Indonesia within the framework of the Coal Kuznets Curve (CKC), using time-series data for the period 1994–2023.
Methods: The study employs an Autoregressive Distributed Lag (ARDL) model with an Error Correction Model (ECM) approach, along with robustness tests using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS).
Results: The results reveal a U-shaped nonlinear relationship between economic growth and coal consumption, indicating that the relationship varies across income levels: at lower income levels, economic growth is associated with declining coal consumption, whereas beyond a certain income threshold, coal consumption rises again. This pattern deviates from the conventional inverted U-shaped Coal Kuznets Curve hypothesis. Population density and industrial activity are also found to significantly increase coal consumption.
Conclusion: Overall, these findings confirm that economic growth in Indonesia has not been accompanied by a reduction in dependence on coal, underscoring the urgent need for structural energy-transition policies that decouple economic growth from fossil-fuel consumption.

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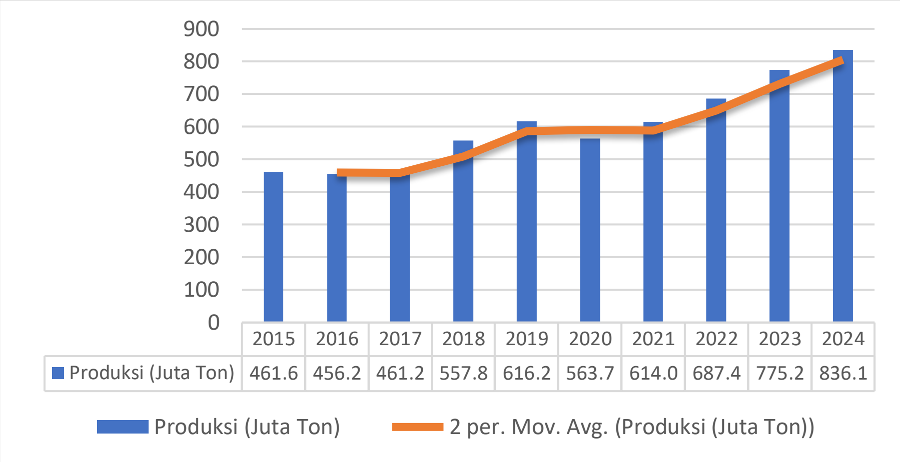
INTRODUCTION

Indonesia is currently classified as an upper-middle-income country by the World Bank, reflecting an increase in economic activity, along with several other countries such as China, Malaysia, and Thailand. This economic growth has been accompanied by a significant reduction in the poverty rate, from around 60% in 1970 to less than 10% in 2021, demonstrating the success of economic development in improving people's welfare. Indonesia also holds a strategic position at the global level, being the world's fourth-most populous country, the seventh-largest economy, the twelfth-largest energy consumer, and the ninth-largest emitter of CO_2 from fuel combustion (IEA, 2022). These conditions indicate that, on the one hand, Indonesia has achieved rapid economic progress, but, on the other hand, it also faces significant challenges in managing energy consumption and carbon emissions sustainably.

Indonesia is also one of the world's largest coal-producing countries. Coal production in Indonesia has shown an increasing trend over the years, with a significant increase in 2024, reaching 836 million tons, an 8% increase from 775 million tons in the previous year (see Figure 1.1, which presents coal production in Indonesia from 2015 to 2024). Coal exports also increased to 555 million tons, representing an increase of approximately 7%. Meanwhile, domestic coal consumption increased to 233 million tons, an increase of approximately 9% compared with the previous year. This trend demonstrates that coal continues to play a significant role in the Indonesian economy (Ministry of Energy and Mineral Resources, 2025).



Source: *Energy Institute*, 2025, processed

Figure 1. Coal Production in Indonesia in 2015 - 2024

The upward trend in coal production is inseparable from the increasing demand for coal in domestic metallurgical industries, such as the iron and steel industry and smelting facilities. However, domestic coal use is still dominated by the electricity sector, which accounts for 85%, followed by various other industries, such as paper, metallurgy, cement, fertilizer, textiles, and others (Directorate General of Mineral and Mineral Resources of the Ministry of Energy and Mineral Resources, 2021). Electricity production in 2024 reached 343,891.75 GWh, an increase of 6.36% compared with electricity production in 2023. In general, coal continues to dominate power generation, contributing approximately 66.43% in 2024, although this represented a slight decrease from the previous year. In addition to coal, natural gas and renewable energy sources, such as hydropower and geothermal energy, also play significant roles, although their respective shares remain relatively small (PT Perusahaan Listrik Negara (Persero), 2025). Overall, Indonesia's electricity energy mix remains dominated by fossil fuels, particularly coal.

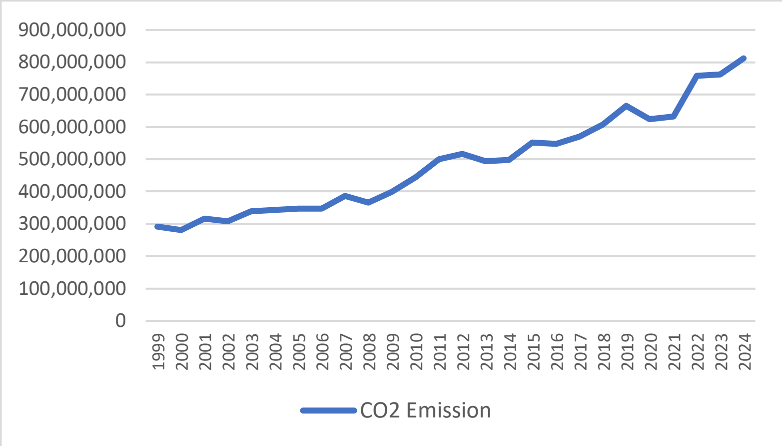
Table 1

Electric Power Production by Type of Fuel Plant

Types of Fuel Generators	2024 Production	2024 Mix	2023 Production	2023 Mix
Coal	228.433,46	66,43%	216.776,86	67,05%
BBM	10.054,41	2,92%	8.576,07	2,65%
Natural Gas	60.686,45	17,65%	55.979,00	17,31%
Geothermal	16.763,21	4,87%	16.935,73	5,24%
Water	21.505,13	6,25%	19.931,87	6,16%
Others	6.449.09	1,88%	5.121,09	1,58%
Total Electric Power Production	343.891,75	100%	323.320,62	100,00%

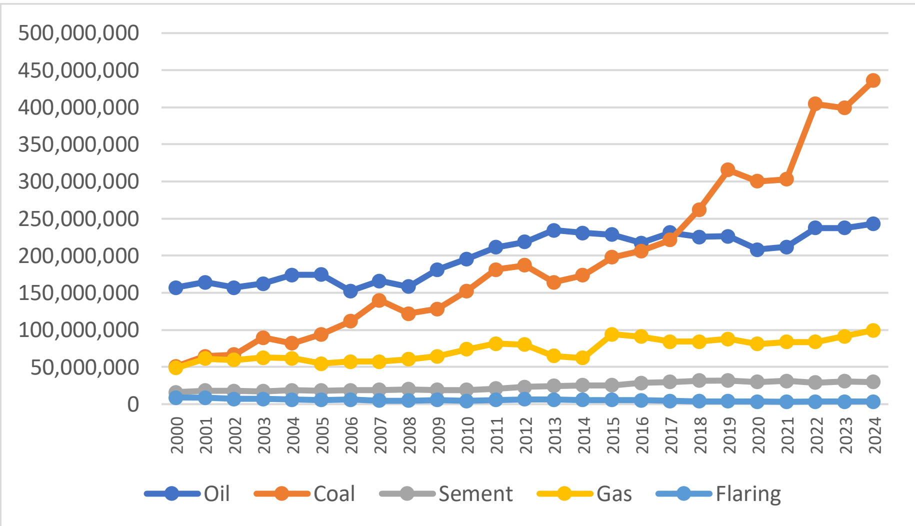
*Source: PT PLN (Persero), 2025, processed

Increased energy use, especially fossil energy sources such as coal, is not only closely related to economic growth but can also cause environmental problems. As economic activity increases, energy consumption also increases, contributing to environmental degradation (Farhani & Balsalobre-Lorente, 2020). Coal, as one of the major energy sources, has a considerable environmental impact because it produces various types of harmful emissions, such as sulfur dioxide, nitrogen oxides, particulate matter, carbon dioxide, and mercury. Among all fossil energy sources, coal is the largest emitter of carbon. This can be seen in China, the world's largest coal user, which experienced a significant increase in CO_2 emissions due to rapidly increasing coal consumption (Balat, 2007). Saboori & Sulaiman (2013) found that the use of fossil energy sources (coal, natural gas, electricity, and petroleum consumption) contributes to increased CO_2 emissions in Malaysia, thus creating a dilemma between economic growth and environmental conservation. Policies aimed at reducing fossil energy consumption can indeed reduce emissions; however, they may also have the potential to slow economic growth. Adekoya et al. (2023) also found that increased coal consumption can lead to higher carbon emissions and environmental degradation. The study also identified a threshold effect, whereby the negative environmental impact of coal consumption becomes substantially greater once coal consumption exceeds a certain level. This indicates that higher coal consumption is associated with a greater risk of environmental damage.



Source: *Our World in Data*, 2025, processed
Figure 2. Annual CO2 Emission Trends in Indonesia 1999 - 2024

Indonesia has also experienced a substantial increase in CO_2 emissions. According to *Our World in Data* (Figure 1.2), CO_2 emissions reached approximately 812 million tonnes in 2024, with coal-related emissions showing the fastest growth and accounting for the largest share compared with oil and natural gas. This indicates that Indonesia's dependence on coal as a primary energy source contributes significantly to increased environmental pressure. While emissions data alone do not establish a direct causal relationship between coal dependence and economic growth, the co-movement of rising coal consumption, expanding industrial output, and growing CO_2 emissions suggests a structural linkage that warrants rigorous empirical analysis. Thus, this pattern reinforces the argument that increased coal consumption is closely associated with increased carbon emissions, as found in previous studies.



*Source: *Our World in Data*, 2025, processed
Figure 3. CO2 Emissions by Energy Source 2000 - 2024

In general, economic growth in the early stages of development tends to increase environmental degradation due to rising energy consumption and industrial activities. As income levels and environmental awareness increase, however, environmental pressures may gradually decline as countries adopt cleaner technologies, improve energy efficiency, and implement stronger environmental policies. This pattern is commonly described by the Environmental Kuznets Curve (EKC), which posits an inverted U-shaped relationship between economic growth and environmental degradation (Li, 2024). The EKC hypothesis has been widely examined across different countries, although the empirical evidence remains mixed. Bilgili et al. (2016), for instance, confirmed the existence of the EKC in OECD countries over the period 1977–2010. Their panel-level results supported the inverted U-shaped relationship, although the evidence was less consistent when individual countries were examined separately. Similar evidence was reported by Danish et al. (2017) for Pakistan, Pata (2018) for Turkey, Zaidi et al. (2019) for APEC countries, and Wang et al. (2024) using data from 147 countries. More recently, Akar et al. (2025) identified an inverted U-shaped EKC pattern in OECD countries during 1990–2020, but not in China and India, where emissions continued to increase alongside economic growth. These findings suggest that the EKC should not be regarded as a universal pattern, as its validity depends on the structural, technological, energy, and institutional characteristics of individual countries.

The EKC framework can be further extended by focusing specifically on coal consumption, leading to the concept of the Coal Kuznets Curve (CKC). Within this framework, coal consumption is expected to increase during the early stages of economic development as industrialization and energy demand expand, but eventually decline after a certain income threshold as economies shift toward cleaner energy sources and more efficient technologies. Erdogan et al. (2024) provide evidence of an inverted U-shaped relationship between economic growth and coal consumption across the 25 largest coal-consuming countries, including Indonesia. Consistent with this finding, Bese et al. (2020) confirmed the CKC hypothesis in Australia and China, identifying an inverted U-shaped relationship between economic growth and coal consumption during 1980–2016 and 1980–2014, respectively. These findings are particularly relevant given the substantial role of coal in the energy systems of both countries. In the Indonesian context, Kurniawan and Managi (2018) also found evidence supporting the EKC hypothesis when coal consumption was used as an indicator of environmental pressure. Their findings indicate that economic growth, urbanization, and trade openness initially contribute to higher coal consumption, while structural changes in the economy can subsequently reduce dependence on coal.

Although the relationship between economic growth, energy consumption, and environmental degradation has been extensively examined through the EKC framework, empirical research specifically addressing coal consumption through the CKC framework remains relatively limited, particularly in Indonesia. Kurniawan and Managi (2018) examined the CKC in Indonesia using data only up to 2014. Since then, Indonesia's energy landscape has undergone substantial changes, including the expansion of captive coal-fired power generation in industrial areas and the development of downstream industries that may influence coal demand. In addition, the previous study did not employ the more recent ARDL-ECM framework, complemented by FMOLS and DOLS robustness tests, nor did it distinguish population density from total population as a separate determinant of coal consumption. These developments create an empirical gap that warrants an updated assessment of the CKC hypothesis in Indonesia.

Therefore, this study extends the existing literature by re-examining the CKC in Indonesia using data through 2023 and incorporating an econometric framework that combines ARDL-ECM estimation with FMOLS and DOLS robustness tests. The study also considers population density as a distinct explanatory factor to provide a more comprehensive understanding of the determinants of coal consumption. By updating the observation period and strengthening the empirical methodology, this study is expected to contribute to the energy economics literature while providing relevant evidence for the formulation of more sustainable energy and environmental policies in Indonesia.

Literature Review and Hypothesis Development

Dynamics of the Economy, Energy, and Carbon Emissions in Indonesia

Indonesia's economic and energy conditions exhibit both growth dynamics and structural challenges in the energy transition. In this context, coal plays an important role in the economic structure, with coal exports being one of the country's largest export commodities in recent years.

In terms of energy, Indonesia's total energy supply has increased rapidly since 2000, with coal experiencing a significant surge to become the largest source of energy, surpassing oil. Access to modern energy has also increased dramatically, as reflected in an electrification ratio that reached 99.92% by 2024. However, this increase has been accompanied by a more than twofold increase in the energy sector's CO_2 emissions since 2000, with more than 70% of the increase coming from coal use. This condition indicates a trade-off between economic growth and increased emissions. Despite this, Indonesia has demonstrated its commitment to climate change mitigation through updates to its Nationally Determined Contribution (NDC) and long-term strategies toward Net Zero Emissions by 2060 or sooner. To achieve this target, strong and integrated efforts are needed across the energy sector (IEA, 2022).

Indonesia has established a relatively comprehensive direction for energy and climate change policies to support the transition to a more sustainable energy system. Through the Enhanced Nationally Determined Contribution (NDC) document, the Indonesian government has established various strategic commitments, including an integrated policy framework through RUEN, RUPTL, the NDC, and RPJMN to support the achievement of Net Zero Emissions by 2060. The government also encourages the development of renewable energy by targeting the use of new and renewable energy (NRE) at least 23% by 2025 and 31% by 2050, as well as implementing biodiesel policies (B20 to B30). The energy subsidy reforms that have been carried out are also an important step in directing fiscal allocations toward more productive sectors, such as education, health, and social assistance for the community. However, despite these advances, significant structural challenges remain in the implementation of the energy transition in Indonesia. Dependence on coal remains very high, as demonstrated by the increase in power generation capacity, particularly through captive power schemes in the industrial sector. In addition, the national energy mix target still provides a considerable share for fossil energy in the long term. The energy transition process is also highly dependent on global support, both in the form of technology transfer and financing. On the other hand, the increasing need for economic development has also contributed to the increase in overall energy consumption (Government of Indonesia, 2022).

Thus, although Indonesia can be said to be on the right track in terms of policy formulation, the current implementation and energy structure indicate that the transition process is still not fully optimal. This reflects the challenge of balancing economic growth and decarbonization efforts, which is an important issue in analyzing the relationship between energy, emissions, and economic development in Indonesia.

STIRPAT

STIRPAT Model (Stochastic Impacts by Regression on Population, Affluence, and Technology) was developed as an improvement of the IPAT model, which initially described only the deterministic relationship between population, affluence, technology, and environmental pressures. The concept of IPAT itself was introduced by (Ehrlich & Holdren, 1971). Perman (2003) summarizes this relationship in the form of the following equation:

$$I = P \times A \times T \qquad 2.1$$

where I represents environmental impact, P represents population size, A represents the level of affluence (GDP per capita), and T represents technology intensity. Increased income tends to increase consumption and environmental pressures, whereas technological efficiency can mitigate these impacts. The IPAT model has limitations because it is deterministic, making it less flexible for empirical statistical analysis. To overcome this limitation, Dietz & Rosa (1994) developed the STIRPAT model by adding a stochastic component, thereby allowing for more realistic and data-based testing of relationships between variables. With this approach, the STIRPAT model can be used to test hypotheses empirically in environmental and economic studies.

In the development of modern research, many studies have used extended STIRPAT models by incorporating a variety of additional variables to capture the complexity of the relationship between economic activity and environmental degradation. This approach no longer relies on a single indicator but integrates other factors, such as energy consumption, economic structure, urbanization, and institutional quality, to improve model accuracy and reduce specification errors. Thus, the extended STIRPAT model is considered better able to comprehensively explain the dynamics of environmental pressure and reflect more realistic empirical conditions. In general, the relationships between the variables in the extended STIRPAT model proposed by Gani (2021) can be formulated as follows:

$$ENVQ = f(FF, EKC, EA, DEM, FC, IQ) \quad 2.2$$

In this model, ENVQ represents environmental quality, while FF reflects the use of fossil fuels, such as coal, oil, and natural gas. The EKC variable includes income (Y) and its squared term (Y^2) to test the nonlinear relationship proposed by the Environmental Kuznets Curve hypothesis, which is also relevant in the context of the Coal Kuznets Curve (CKC). Furthermore, EA describes economic activity, DEM represents population density, FC captures environmental conditions through forest cover, and IQ reflects institutional quality, such as government effectiveness, law enforcement, and international environmental commitments. The combination of these variables is used to construct a more comprehensive model for explaining the factors that affect environmental quality.

In the context of this study, the STIRPAT framework is operationalized as follows: the Population (P) component is represented by Population Density (PD), reflecting demographic pressure on coal consumption; the Affluence (A) component is represented by GDP per capita and its squared term (GDP^2) to capture the nonlinear CKC relationship; and the Technology (T) component is proxied by the Industrialization Rate (IND), which reflects the intensity of fossil-fuel-dependent industrial activity. This mapping ensures that each STIRPAT dimension is explicitly addressed in the empirical model.

***Environmental Kuznets Curve* (EKC)**

Grossman & Krueger (1991) explain that the Environmental Kuznets Curve (EKC) hypothesis describes an inverted U-shaped relationship between economic growth and environmental quality. In the early stages of development, increases in economic activity tend to worsen environmental conditions because of high energy consumption and the dominance of fossil fuel use. However, as income levels increase and economic progress occurs, structural transformation toward cleaner technologies and more environmentally friendly economic sectors may take place. In addition, the implementation of increasingly stringent environmental regulations can also play a role in reducing emission and pollution levels (Miyan et al., 2026).

Most previous studies have analyzed the EKC hypothesis using quadratic models to capture nonlinear relationships between income levels and environmental degradation. Bilgili et al. (2016) explained that, in general, the relationship can be formulated as follows:

$$E = f(Y, Y^2, Z) \quad 2.3$$

In this formulation, environmental variables reflect the level of pollution or environmental degradation, while per capita income is used to represent the level of economic well-being. The addition of the squared income term aims to identify nonlinear relationship patterns, specifically to test whether the relationship follows the inverted U-shaped pattern described by EKC theory.

In line with this framework, various empirical studies have tested the existence of the EKC using different indicators of environmental degradation. In general, the results show support for the EKC hypothesis, characterized by a nonlinear relationship between economic growth and environmental degradation. Using CO_2 emissions as the dependent variable, Bilgili et al. (2016) found that increasing GDP in the early stages of development tends to increase emissions, as observed in OECD countries and Pakistan. Similar results were also reported by Pata (2018) in Turkey, Zaidi et al. (2019) for APEC countries, and Wang et al. (2024) using data from 147 countries. These studies confirm the inverted U-shaped pattern, although the relationship is influenced by other factors, such as globalization, financial sector development, and population density. Meanwhile, Akar et al. (2025) found that the EKC applies only to OECD countries and is not observed in China and India, indicating that the EKC is not a universal phenomenon but is strongly influenced by the level of technological advancement, energy structure, and stage of industrialization in each country. The use of indicators other than CO_2 emissions has also been examined in various empirical studies. In particular, the Ecological Footprint (EF) has increasingly been used as an environmental indicator because it is considered more comprehensive than a single measure of CO_2 emissions. A number of studies, such as Luo & Sun (2024), Khalid et al. (2025), and Özbek & Naimoğlu (2025), show that the relationship between GDP and EF is nonlinear and follows the Environmental Kuznets Curve (EKC) pattern.

The Environmental Kuznets Curve (EKC) hypothesis provides an important framework for understanding the relationship between economic growth and nonlinear environmental degradation. Although many studies have found evidence of an inverted U-shaped pattern, empirical results show that the applicability of the EKC is not universal and is highly dependent on the characteristics of each country. In addition, the use of more comprehensive environmental indicators, such as the Ecological Footprint, further enriches the analysis of the dynamics of this relationship. Therefore, the study of the EKC remains relevant, particularly in the context of developing countries such as Indonesia, to better understand the interaction between economic growth, energy consumption, and environmental pressures.

Coal Kuznets Curve **(CKC)**

The Coal Kuznets Curve (CKC) can be understood as an extension of the Environmental Kuznets Curve (EKC) concept that focuses more specifically on the role of coal consumption in relation to economic growth. Erdogan et al. (2024) explain that the CKC concept was developed to more specifically analyze the relationship between economic growth and coal consumption. Several empirical studies, such as Abbasi et al. (2022), show that fossil fuel consumption has a positive and significant impact on CO_2 emissions, thereby contributing to a decline in environmental quality. Thus, it is not sufficient to focus solely on emissions as an outcome; attention should also be directed toward their primary sources, particularly coal consumption. Therefore, analyzing the factors that affect coal consumption is increasingly important, especially for supporting the formulation of more sustainable energy transition policies.

Several studies have examined the existence of the Coal Kuznets Curve (CKC) in the relationship between economic growth and coal consumption. The results of Erdogan et al. (2024) show that coal consumption follows an inverted U-shaped relationship with economic growth within the CKC framework, whereby consumption increases during the early stages of development and decreases after reaching a certain level of income in the 21 countries with the highest levels of coal dependence from 1997 to 2021. Similar findings were reported by Bese et al. (2020) for Australia and China, confirming the existence of the CKC during the study periods for both countries. In addition, Kurniawan and Managi (2018) found that the CKC also applies to Indonesia, where economic growth, urbanization, and trade openness encourage coal consumption during the early stages of development, while changes in the economic structure contribute to reducing such consumption in the long run.

Research on the CKC remains limited, particularly in the Indonesian context. As a country with a high dependence on coal, Indonesia provides an important case for examining the relationship between economic growth, coal consumption, and environmental pressures. Therefore, analyzing the CKC in the Indonesian context is necessary to provide a more precise understanding of these relationships and to support the formulation of sustainable energy transition policies.

Conceptual Framework

To clarify the relationship between variables in this study, this study develops a conceptual framework as a basis for analyzing the relationship between economic growth and coal consumption.

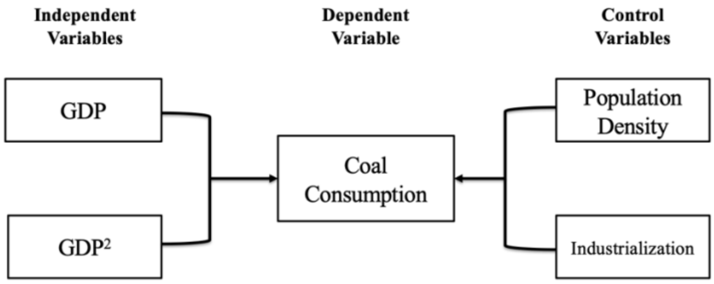


Figure 4. Conceptual Framework

The conceptual framework of this study describes the dependent variables, namely coal consumption (COAL) which is influenced by economic growth represented by GDP and the square of GDP (GDP^2) to capture non-linear relationships according to the CKC hypothesis. In addition, coal consumption is also influenced by control variables, namely population density and industrialization rate, which reflect demographic, structural, and economic factors. Thus, this model is used to analyze how economic and non-economic factors simultaneously affect the dynamics of coal consumption.

Hypothesis Development

The Effect of Economic Growth on Coal Consumption

Based on the theoretical framework *Coal Kuznets Curve* (CKC), economic growth is suspected to have a non-linear relationship with coal consumption. In the early stages of development, the increase in economic activity tends to encourage an increase in coal consumption as the main energy source. However, once it reaches a certain level of income, coal consumption is expected to decline as there is a shift towards cleaner energy, improved energy efficiency, and stricter environmental policies. Therefore, the hypothesis of this study is formulated as follows:

H1: *The Coal Kuznets Curve (CKC) hypothesis applies in Indonesia, namely that there is an inverse U-shaped non-linear relationship between economic growth and coal consumption*

The Effect of Control Variables on Coal Consumption

Population density, defined as the number of inhabitants per square kilometer, is suspected to increase energy demand due to intensified economic activity and consumption needs in more densely populated areas. It is important to distinguish population density from total population: density can increase either through absolute population growth or through spatial concentration (migration and urbanization toward specific areas), both of which can independently drive energy demand. The level of industrialization is also expected to encourage an increase in coal consumption because the industrial sector is generally still dependent on fossil-based energy. Therefore, the second hypothesis is formulated as follows:

H2: *Population density and industrialization have a significant effect on coal consumption in Indonesia.*

METHOD

This study used Indonesian time series data for the period 1994–2023 as a research sample to analyze the relationship between economic growth and coal consumption in the framework Coal Kuznets Curve (CKC). The variable consumption of coal (COAL) is obtained from Our World in Data, while the variables of economic growth (GDP), population density (PD) and industrialization rate (IND are sourced from World Bank. The selection of the period and data source is based on the availability of consistent data and relevance in describing the dynamics of energy consumption and economic development in Indonesia.

It should be noted that the model in this study is limited to GDP per capita, population density, and industrialization rate as the core explanatory variables, in addition to the renewable energy variable that appears in the theoretical model but was excluded from the final estimation due to data limitations and multicollinearity concerns. Future research may benefit from incorporating additional variables such as institutional quality, trade openness, and technological innovation to provide a more comprehensive explanation of coal consumption dynamics.

This study uses *Autoregressive Distributed Lag* (ARDL) model to analyze the short-term and long-term relationship between economic growth and coal consumption. This method was chosen because it is able to accommodate variables with different levels of integration (I(0) and I(1)) and allows cointegration testing through the bounds test by using bounds testing approach as developed by Pesaran et al. (2001), by testing the coefficient of the level variable coefficients in the model. The ARDL approach is preferred over the Vector Error Correction Model (VECM) for several reasons. First, VECM requires all variables to be integrated at the same order (I(1)), whereas ARDL can handle a mixture of I(0) and I(1) variables, which is more flexible and appropriate for this study's data. Second, ARDL provides more reliable results in small samples, such as the 30-year time series used in this study, whereas VECM estimation requires more degrees of freedom. Third, ARDL allows for different lag lengths for each variable, providing a more parsimonious specification. These advantages make ARDL the most suitable method for this analysis.

After confirming that all variables are stationary on orders I(0) and I(1), the next step is to determine the optimal lag length to be used in the ARDL model. This lag determination is crucial because of the statistical value in ARDL estimation, especially in cointegration testing through bounds test, is very sensitive to lag selection. Therefore, proper lag selection is necessary to avoid model specification errors, either Underfitting or Overfitting. In this study, the determination of optimal lag was carried out using information criteria Intelligence Information Criterion (AIC), which tends to choose a more comprehensive combination of lag to capture the dynamics of relationships between variables. Based on the results of the selection, the best ARDL model used in the next estimate was obtained.

Regression Model

Mathematically, the basic model in this study can be written as follows:

$$COAL_t = f(GDP_t, GDP_t^i, PD_t, IND_t) \tag{3.1}$$

For the purposes of empirical estimation, the entire variable is transformed into a natural logarithmic form, so that the model becomes:

$$\ln COAL_t = \beta_0 + \beta_1 GDP_t + \beta_2 (\ln GDP_t)^2 + \beta_3 \ln PD_t + \beta_4 \ln IND_t + \varepsilon_t \tag{3.2}$$

Furthermore, to capture the short-term and long-term dynamics, the model is estimated using the ARDL approach in the form of *the Unrestricted Error Correction Model* (UECM) as follows:

$$\begin{aligned}\Delta \ln COAL_t = \beta_0 &+ \sum_{i=1}^{p} \beta_{1i} \Delta \ln COAL_{t-i} + \sum_{i=0}^{q1} \beta_{2i} \Delta \ln GDP_{t-i} \\ &+ \sum_{i=0}^{q2} \beta_{3i} \Delta (\ln GDP_{t-i})^2 + \sum_{i=0}^{q3} \beta_{4i} \Delta \ln PD_{t-i} \\ &+ \sum_{i=0}^{q4} \beta_{5i} \Delta \ln IND_{t-i} + \sum_{i=0}^{q5} \beta_{6i} \Delta \ln REN_{t-i} + \lambda_1 \ln COAL_{t-1} \\ &+ \lambda_2 \ln GDP_{t-1} + \lambda_3 (\ln GDP_{t-1})^2 + \lambda_4 \ln PD_{t-1} \\ &+ \lambda_5 \ln IND_{t-1} + \varepsilon_t\end{aligned} \tag{3.3}$$

In equation 3.3, the β coefficient represents the short-term dynamics through the first difference of each variable, while the λ coefficient represents the long-term relationship or equilibrium between variables in the level.

RESULTS AND DISCUSSION

Result

This study uses data Time series for Indonesia with an observation period of 1994 to 2023. The variables used in the empirical analysis as well as descriptive statistical results are presented in Table 2.

Table 2
Descriptive Statistics

Variable	Units	Obs.	*Mean*	*Std. Dev.*	*Min.*	*Max.*
Coal Consumption	kWh/Capita	30	1.660,83	1.046,003	291,55	4.362,9
Gross Domestic Product (GDP)	US$ constant 2015 per capita	30	2.701,26	796,29	1.767,51	4.192,65
Population Density (PD)	Population/km2	30	129,13	12,66	108,52	148,57
Industrialization Rate (IND)	% of GDP	30	43,09	3,007	38,23	48,06

The descriptive statistical results in Table 2 show that all variables have the same number of observations, which is 30, which indicates that there is no data lost during the observation period 1994–2023. The coal consumption variable has an average of 1,660.83 kWh/capita with a relatively high level of variation, reflected in the standard deviation of 1,046.00. This shows that there are considerable fluctuations in fossil energy consumption in Indonesia. Gross Domestic Product (GDP) per capita averaged 2,701.26 (constant US$ 2015) with moderate variations, reflecting relatively stable economic dynamics. The population density showed an average value of 129.13 inhabitants/km^2 with a low standard deviation, indicating a small degree of variation. The industrialization rate has an average of 43.09% with relatively limited variation, which indicates the stability of the industrial structure.

Table 3
Panel Unit root test results

Variable	*Level*		*1st Difference*	
	Constant	**Constant + Trend**	**Constant**	**Constant + Trend**
LnCoal	-1,728	-2,290	-4,098***	-4,329**
LnGDP	0,437	-2,781	-3,788***	-4,147**
LnGDP2	0,535	-2,740	-3,721**	-4,149**
LnPD	-1,056	-1,827	-3,680**	-3,705**
LnIND	-1,545	-2,745	-6,196***	-6,366***

Note: ***, **, and * show significance levels at 1%, 5%, and 10% levels, respectively.

Based on the results of these descriptive statistics, the analysis was continued with a unit root test. Unit root testing is an important stage in time-series data analysis to ensure that the variables used are stationary, so that the resulting model does not produce a spurious regression (Mohamed et al., 2024). Stationarity indicates that the mean, variance, and covariance of a variable remain constant over time (Bhattacharya et al., 2015). This study uses the Augmented Dickey-Fuller (ADF) unit root test to identify the stationarity of the data.

The test results presented in Table 3 show that all variables are nonstationary at the level, under both the constant-only and constant-and-trend specifications, as indicated by statistically insignificant test statistics. However, after first differencing, all variables became stationary at the 1% and 5% significance levels. This indicates that all variables in this study are integrated of order one, or I(1). These findings suggest that although the variables are nonstationary in the short term, there may be a long-term relationship among them. Therefore, estimation methods that account for cointegration, such as the Autoregressive Distributed Lag (ARDL) approach, are relevant for the subsequent analysis.

Next, after confirming that all variables are integrated of order one, or I(1), the next step is to determine the optimal model specification through lag-length selection. In the Autoregressive Distributed Lag (ARDL) approach, the optimal lag length is selected using information criteria, such as the Akaike Information Criterion (AIC), which aims to identify the best-fitting model while balancing goodness of fit and model complexity. In this study, the maximum lag length was limited to two lags, considering the relatively limited number of observations. Using excessively long lags in a small sample can reduce the degrees of freedom and the efficiency of the estimation. Therefore, a more parsimonious approach was chosen to maintain model stability and avoid overfitting. Based on the lag-selection results using the information criterion, the optimal ARDL model obtained was ARDL (1, 2, 0, 0, 2). The selected model indicates that the dependent variable is affected by one lag of its own, while the independent variables have different lag structures according to their respective dynamic characteristics. This flexibility in lag determination is one of the main advantages of the ARDL approach over other methods, as it allows each variable to have an optimal lag length without requiring all variables to have the same lag structure.

Table 4

Results of the Bound Test Cointegration Test

Statistics F	Value	k
	4,936	4
Critical Value Bounds	I(0)	I(1)
10%	2,792	4,174
5%	3,474	5,090
1%	5,222	7,418

Based on the optimal ARDL model obtained through lag-length selection using information criteria, the next stage is to test for the existence of a long-term relationship among the variables in the model. This test is conducted using the bounds testing approach to determine whether the variables under study have a cointegration relationship. The test results show that the F-statistic value of 4.936 is greater than the critical value of the upper bound at the 10% significance level, which is 4.174. Thus, the null hypothesis stating that there is no long-term relationship is rejected. These results indicate the existence of a cointegration relationship among the variables in the model, suggesting that the variables under study have a long-term equilibrium relationship. Therefore, the Autoregressive Distributed Lag (ARDL) approach in the form of an Error Correction Model (ECM) can be used to analyze short-term and long-term relationships simultaneously.

Table 5 presents the results of the ARDL-ECM estimation for the dependent variable. The coefficient of ΔlnCoal ECT(-1) is negative at −0.872 and significant at the 1% level, indicating an adjustment mechanism toward long-term equilibrium. This means that approximately 87.2% of short-term disequilibrium is corrected within a single period. In the long term, LnGDP has a significant negative effect, whereas LnGDP^2 has a significant positive effect on LnCoal, indicating a U-shaped relationship. In addition, LnPD and LnIND have significant positive effects on coal consumption. In the short term, ΔLnGDP and ΔLnGDP(-1) have significant positive effects, whereas ΔLnIND has a significant negative effect.

Table 5

ARDL-ECM Model Estimation Results

Dependent variable: ΔlnCoal				
	β	s (β)	Statistics t	*p-value*
$\boldsymbol{ECT_{t-1}}$	-0,872***	0,194	-4.49	0,000
Long Term	β	s (β)	Statistics t	*p-value*
LnGDP	-50,44***	10,43	-4,83	0,000
LnGDP2	3,07***	0,66	4,61	0,000
LnPD	13,34***	2,10	6,34	0,000
LnIND	3,14***	0,99	3,17	0,005
Short Term	β	s (β)	Statistics t	*p-value*
$\boldsymbol{\Delta LnGDP_t}$	3,36***	0,86	3,89	0,001
$\boldsymbol{\Delta LnGDP_{t-1}}$	2,07**	0,96	2,15	0,046
$\boldsymbol{\Delta LnIND_t}$	-1,52*	0,75	-2,02	0,058
$\boldsymbol{\Delta LnIND_{t-1}}$	-1,07	0,71	-1,51	0,148
R2 = 0.632				
Adjusted R^2 = 0.4485				
Log likelihood = 30.408184				
Root MSE = 0.1019				

Number of observations = 28
Serial Correlation = No autocorrelation (Prob > chi2 = 0.8883)
Heteroscedasticity = No heteroscedasticity (Prob > chi2 = 0.6938)
Note: indicates the first differentiation of the variable. and each shows a coefficient and standard error. , **, and * show significance at the 1%, 5%, and 10% levels.$\boldsymbol{\Delta\beta}$**s** ($\boldsymbol{\beta}$)

Figure 5 below presents the results of the model parameter stability test using the CUSUM method for the ARDL-ECM model. Based on the graph, the CUSUM line remains within the critical bounds at the 5% significance level throughout the observation period. This indicates that the model parameters are stable, with no indication of structural instability during the study period. Thus, the ARDL-ECM model used in this study satisfies the stability assumption and is suitable for further analysis.

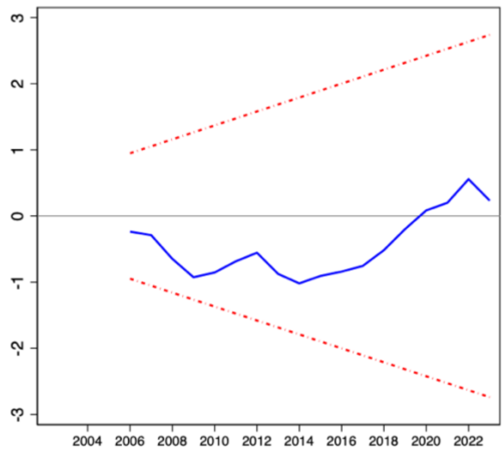


Figure 5. CUSUM Graph on ARDL-ECM Model

As part of the robustness check, this study employs the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) methods to verify the consistency of the long-run estimation results. The DOLS approach has the advantage of producing consistent and efficient estimators, particularly in small samples, by correcting for potential biases arising from endogeneity and serial correlation.

Table 6
FMOLS & DOLS Robustness Test Results

Variable	FMOLS Coefficients	*P-Values*	DOLS Coefficients	*P-Values*
lnGDP	-9,67*	0,053	-57,39***	0,000
lnGDP2	0,55*	0,082	3,54***	0,000
lnPD	11,05***	0,000	12,96***	0,000
lnIND	2,77***	0,000	4,69***	0,000
Cons	-15,15	0,428	158,23	0,000
R2		0,926		0,989
Adjusted R2		0,914		0,973

Table 6 presents the robustness test results using FMOLS and DOLS methods. In general, the estimation results show that the independent and control variables in this study have consistent directions of influence on the dependent variable, namely coal consumption (LnCoal), although there are differences in the levels of statistical significance between the two methods. In the long term, the FMOLS and DOLS estimation results show that the LnGDP variable has a negative and statistically significant effect on coal consumption, while $LnGDP^2$ has a positive and statistically significant effect, with differences in the levels of significance between the two methods. This indicates a nonlinear relationship between economic growth and coal consumption. In addition, the population density (LnPD) and industrial activity (LnIND) variables consistently show positive and statistically significant effects on coal consumption in both estimation methods. These findings indicate that population growth and increased industrial activity contribute to rising demand for coal-based energy. In terms of goodness of fit, the DOLS model shows better performance than the FMOLS model, with an R^2 value of 0.989 and an adjusted R^2 of 0.973, compared with 0.926 and 0.914, respectively, for FMOLS. This suggests that the DOLS model has a greater ability to explain variations in coal consumption. Overall, the consistency in coefficient directions across the FMOLS, DOLS, and main ARDL-ECM models indicates that the estimated results are robust and relatively insensitive to differences in estimation methods. Thus, the results of this robustness test strengthen the validity of the main findings of this study.

Discussion

Analysis of the dynamics of coal consumption in Indonesia during the period 1994–2023 reveals a strong relationship between economic growth, population structure, and the acceleration of industrialization. Based on the estimation results in Table 4.4, the model demonstrates strong statistical performance and a highly responsive long-term adjustment mechanism, indicating that Indonesia's economic structure responds relatively quickly to changes in the determinants of coal consumption, with only approximately 12.8% of the disequilibrium remaining to be corrected in the following period. The stability of this model is further supported by the results of the robustness test in Table 4.5, which demonstrate consistency in the direction of the relationships among the variables across both the FMOLS and DOLS methods.

The most significant finding in this study is the confirmation of a U-shaped relationship between economic growth and coal consumption, which contrasts with the inverted U-shaped curve predicted by the conventional Coal Kuznets Curve (CKC) hypothesis. This pattern can be explained through several interconnected economic mechanisms. In the early stages of income growth, roughly corresponding to the 1994–2005 period, improvements in energy efficiency, shifts toward less energy-intensive services, and early policy incentives for cleaner energy led to a relative decline in coal intensity. However, as Indonesia entered a phase of accelerated industrial expansion driven by commodity booms, downstream processing of natural resources, and nickel-smelting industries after 2010, the capital-intensive and coal-dependent nature of these industries generated a structural "rebound" in coal demand. This rebound was further reinforced by the lock-in effect of investment in coal-related infrastructure, which created path dependence in energy supply choices. Therefore, the U-shaped outcome reflects not a failure of economic progress, but rather the structural heterogeneity of Indonesia's growth model, in which different income periods are associated with qualitatively different energy regimes.

The difference in the results can be explained by structural changes in Indonesia's energy system and economy that have strengthened dependence on coal. Indonesia's industrial energy landscape is currently experiencing rapid growth that remains dominated by fossil fuels, particularly coal, which has the potential to threaten economic stability as well as the country's commitments to addressing climate change. During the period from 2019 to 2024, captive coal-fired power generation capacity increased sharply. The rapid expansion of captive coal-based electricity generation in Indonesia has been driven by the needs of the industrial sector, particularly in remote mining areas, for a large, stable, and reliable supply of electricity that cannot be fully met by the public electricity grid. This growth is inseparable from Indonesia's industrial downstreaming strategy, which encourages the expansion of energy-intensive sectors such as metal processing, nickel smelting for electric vehicle batteries, pulp and paper, chemicals, cement, and textiles, all of which collectively strengthen dependence on coal-based energy (IESR, 2026).

The positive and statistically significant effect of population density indicates that population growth in Indonesia has also contributed to increased energy demand. These results reinforce the argument that population density can drive higher coal consumption, particularly during stages of economic development that remain dependent on fossil fuels. Similarly, industrial activity has a positive and statistically significant long-term effect, indicating that increasing industrialization contributes to higher coal consumption in Indonesia.

Overall, these findings provide crucial and specific policy signals. The U-shaped CKC pattern and the confirmed roles of industrialization and population density in driving coal consumption point to the necessity of targeted and operational policy interventions. Specifically, the government should: (1) accelerate the mandatory retirement of captive coal-fired power plants in the industrial sector by establishing binding phase-out timelines and coupling them with subsidized renewable energy alternatives, such as geothermal, solar, and biomass, for industrial clusters; (2) redesign industrial development incentives within Special Economic Zones (SEZs) to condition fiscal benefits on the adoption of clean energy technologies, thereby decoupling industrial growth from coal dependence; (3) strengthen carbon pricing mechanisms and expand the Emissions Trading System (ETS), currently piloted in the power sector, to include major industrial emitters; and (4) direct financing for the transition of coal-dependent industries, such as Just Energy Transition Partnership (JETP) funds, toward retraining coal-region workers and developing clean energy infrastructure in coal-dependent provinces. The consistency of results across ARDL, FMOLS, and DOLS confirms that, without these structural interventions, future economic growth in Indonesia will continue to be locked into high-coal-consumption trajectories, moving the country further from its Net Zero 2060 target.

CONCLUSION

This study aims to test the Coal Kuznets Curve (CKC) hypothesis by analyzing the dynamic relationship between economic growth and coal consumption in Indonesia using annual time-series data for the period 1994–2023. In addition, this study examines the influence of economic growth, population density, and industrial activity on coal consumption. To ensure robust results, this study uses the ARDL-ECM approach to capture short-term and long-term dynamics, complemented by FMOLS and DOLS estimations as robustness tests.

The empirical results show that the CKC hypothesis in Indonesia exhibits a U-shaped pattern, in which economic growth during the early stages is associated with declining coal consumption, but beyond a certain income threshold, coal consumption resumes its upward trajectory. In addition, population density and industrial activity have positive and statistically significant effects on coal consumption, demonstrating that demographic concentration and the expansion of energy-intensive industries are important structural drivers of coal demand. The results of the robustness tests using FMOLS and DOLS confirm the consistency of these findings. From a theoretical perspective, this study contributes to the CKC literature by demonstrating that the inverted U-shaped hypothesis is not universal and may be reversed in resource-rich, industrializing economies where coal-infrastructure lock-in and downstream industrial expansion dominate energy-system dynamics. Overall, the results of this study indicate that coal consumption in Indonesia is strongly influenced by structural factors; therefore, the transition to cleaner energy continues to face major challenges, particularly in the industrial and electricity sectors. Future research is recommended to extend the analysis by incorporating more comprehensive environmental indicators, such as the Ecological Footprint, as well as institutional quality variables (e.g., regulatory quality and control of corruption) and the share of renewable energy in the energy mix, which may reveal additional policy leverage points for accelerating Indonesia's energy transition.

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AUTHOR CONTRIBUTION STATEMENT

Widya Wahyuni: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft Preparation. Deni Kusumawardani: Data Curation, Visualization, Supervision. All authors have read and agreed to the published version of the manuscript.

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