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# Modeling Carbon Emissions and Energy Transition in the Context of Indonesia's Economic Expansion

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**ABSTRACT**

This study looks at how economic growth, renewable energy use, and carbon dioxide emissions interact in Indonesia's energy plans. It uses data from 1990 to 2023 and a method called ARDL bounds testing to study both long-term and short-term changes in these areas. The results show that economic growth increases $CO_2$ emissions, but using renewable energy helps reduce this effect. This highlights the importance of renewables for low-carbon growth. The study also finds that $CO_2$ emissions lead to more renewable energy use, suggesting that environmental concerns, not just economic growth, influence energy policies in Indonesia. These findings support the idea that as economies grow, they can become more environmentally friendly. However, Indonesia's current efforts to cut emissions may not be enough to meet climate goals due to infrastructure and policy challenges. This study suggests the need for new policies, better energy grids, stronger accounting-based transparency in carbon markets, and cooperation between public and private sectors to speed up the shift to sustainable energy. Indonesia's experience offers important lessons for other developing countries trying to balance economic growth with environmental care.

**Keywords:** Economic Growth, Renewable Energy, Carbon Emissions, Environmental Kuznets Curve, Indonesia
**JEL Classifications:** Q43, Q56, Q01, O44

## 1. INTRODUCTION

In 2024, Indonesia's economy experienced a growth rate of 5.03%, which fell short of the anticipated 8% target, despite the implementation of monetary and fiscal stimulus measures (Reuters, 2025). This outcome highlights the tension between a nation's growth aspirations and its structural limitations. Concurrently, the government announced plans to expand power capacity by 71 GW over the next decade, with a focus on renewable energy sources, such as solar, hydro, and geothermal (Antara News, 2023). However, the actual deployment of renewable energy (RE) remains at approximately 15% of the energy mix, significantly below the 2025 target of 23% (Associated Press, 2025). The key challenges include project viability, regulatory uncertainty, and financial constraints. In this context, the adoption of robust Accounting Management Systems (AMS) becomes critical. AMS can enhance cost tracking, allocate capital more efficiently, and improve accountability in renewable energy projects. By integrating financial performance monitoring with sustainability reporting, AMS offers a mechanism to mitigate risks associated with project financing and ensure alignment with national climate targets. Additionally, large-scale energy and food estate projects in regions such as Kalimantan and Papua have raised environmental concerns owing to deforestation and the disruption of indigenous lands. Indonesia aims to reduce greenhouse gas emissions by up to 43.2% with international support by 2030 and has initiated carbon market reforms to facilitate the sale of carbon credit certificates to global buyers. Effective implementation of such reforms requires transparent accounting practices. Here, AMS plays a role not only in financial reporting but also in verifying carbon credit transactions, ensuring credibility in international markets. These developments underscore the policy paradox Indonesia faces, Advancing an ambitious energy transition and climate agenda, while balancing the competing demands of economic growth and environmental protection.

The relationship between economic growth (EG), renewable energy (RE) and carbon dioxide ($CO_2$) emissions has emerged as a significant research topic given climate change and sustainable development. Since the world is constantly pursuing EG while simultaneously focusing on the welfare of the environment, it is crucial to establish such connections. Recent literature provides a clear picture regarding the relationship between these factors and stresses that the policies are needed to be more effective (Shahbaz et al., 2023). Nonetheless, Indonesia is one of the world's largest industrialized countries and has set aggressive climate targets, making it a good example. Indonesia's new and renewable energy (NRE) – a policy that seeks to eliminate the use of nuclear and fossil energy sources and embrace RE sources has received wide recognition across the globe (Renn and Marshall, 2016). The purpose of this research is to assess the ability of Indonesia's strategy to untie EG from $CO_2$ emissions, with a particular emphasis on RE use.

Global initiatives aimed at mitigating greenhouse gas (GHG) emissions have not yielded significant success, as evidenced by the increasing levels of $CO_2$ emissions, which have profound implications for climate change. The challenge of achieving economic growth (EG) while concurrently reducing carbon dioxide ($CO_2$) emissions—commonly referred to as decoupling—remains a pivotal issue in the discourse on sustainable development. Renewable energy (RE) is widely considered a viable pathway to achieve this objective. However, the interaction between EG, RE, and $CO_2$ emissions is highly complex and context-dependent. Indonesia's commitment to energy transition is reflected in its New and Renewable Energy (NRE) policy, one of the most assertive in Southeast Asia. While this policy has significantly enhanced RE generation capacity in recent years, its overall impact on national emissions and economic dynamics remains a subject of debate. Critics, such as Sinn (2012), have highlighted that the intermittency of RE sources, coupled with inadequate energy storage infrastructure, could undermine emissions reduction efforts. Against this backdrop, this study contributes to addressing the knowledge gap by empirically examining how Indonesia's shift to RE is influencing its carbon trajectory and what insights this holds for other emerging economies.

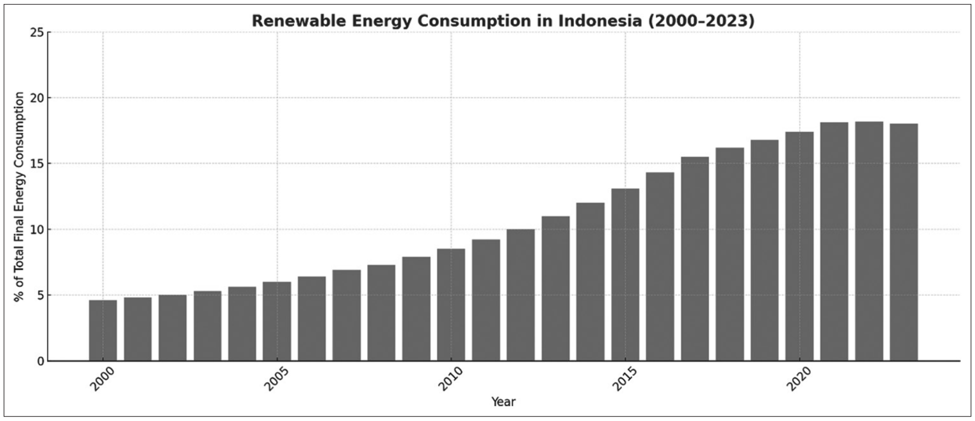
Figure 1 depicts the increasing trend in renewable energy (RE) consumption in Indonesia from 2000 to 2023. The proportion of RE in the nation's total final energy consumption has risen consistently, reaching approximately 18.03% in 2023. Despite this progress, the figure remains below the national target of 23% by 2025, underscoring the necessity for accelerated adoption and policy enhancement. The interrelationship between economic growth (EG), RE, and $CO_2$ emissions is inherently complex. Historically, economic growth has been associated with increased fossil energy consumption and emissions. However, recent shifts towards RE indicate the potential for partial decoupling. As RE capacity has expanded in Indonesia, there has been some reduction in fossil fuel dependency, suggesting environmental benefits. Nonetheless, the relationship remains intricate and non-linear.

Figure 2 illustrates the trajectory of Indonesia's $CO_2$ emissions from 2000 to 2023, highlighting a long-term upward trend with recent indications of stabilization. Although emissions increased steadily from 338.4 million metric tons in 2000 to over 670 million metric tons in 2023, the most recent data suggest a marginal annual increase, indicating potential stabilization. Nevertheless, the current rate of emissions reduction appears inadequate to achieve the country's climate objectives under the Paris Agreement. Several studies (e.g. Dehghan Shabani, 2024; Keh et al., 2024) identify institutional barriers, policy fragmentation, and limited human capital as constraints impeding emissions reduction, despite advancements in renewable energy. Consequently, while Indonesia has made significant progress in expanding renewable energy, the overall impact on emissions reduction remains modest. This underscores the necessity for comprehensive strategies that integrate technological innovation, policy consistency, and capacity building (BMWK, 2021).

Several reasons led Indonesia to be considered a perfect case for the analysis. First, it is one of the largest economies in Asia and an emerging country in the world; therefore, the environmental policies it adopts are of international importance. Second, Indonesia is one of the leading countries that has embarked on an aggressive energy transition policy known as new and renewable energy (NRE). This policy seeks to eliminate nuclear power and fossil energy while at the same raising the share of RE sources to a very high level (Renn and Marshall, 2016). Third, Indonesia has ambitious climate goals, including the reduction of GHG emissions by up to 65% by 2030 compared to the 1990 levels, as well as a zero-carbon economy in the coming two decades. The success or failure of Indonesia in achieving these goals while simultaneously sustaining economic development is quite informative to other developed and emerging economies.

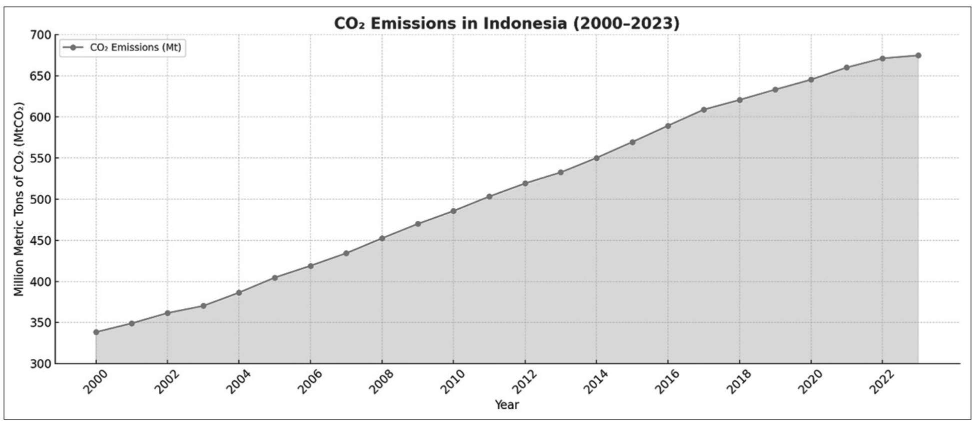
Following the mixed results regarding the influence of EG and RE on $CO_2$ emissions, this study analyzed the nexus of economic progress on the level of $CO_2$ emissions. Due to the rapid industrialization and enhanced energy demand, which are regarded as the backbone of the economy's performance in Indonesia, it is now time to empirically analyze whether the rapidly evolving economic prosperity contributes to the environmental quality of the country. Despite economic growth in the recent past, this research also observed a rapidly increasing level of green energy. This has led to an emphasis on the role of RE in environmental quality. Although most of the existing literature focuses on the critical role of green energy in economic development, recent trends have ignored the importance of green energy in environmental quality,

**Figure 1:** Renewable energy consumption in Indonesia




Source: World Bank (2023)

**Figure 2:** $CO_2$ Emissions in Indonesia




Source: World Bank (2023)

particularly in Indonesia. Therefore, a timely examination of the issue could be beneficial to policymakers as well as scholars.

This study looks at the links between economic growth (EG), renewable energy (RE) use, and $CO_2$ emissions. However, there are some important gaps in the research. First, most studies focus on rich countries and emerging markets, ignoring places like Indonesia. Second, while many studies talk about these links, the effects of EG and RE use on $CO_2$ emissions are still unclear and debated. So, it's important to study these links more, especially in Indonesia. Lastly, more research is needed on how RE and $CO_2$ emissions, economic growth, and energy balance might affect each other in complex ways. This research has several implications for the existing literature in the following ways. Firstly, it offers a detailed, consistent and time series analysis of Indonesia's energy transition, thus building on and updating previous works such as (Adedoyin et al., 2023). Second, it uses a more sophisticated econometric analysis to unravel the interconnections between EG, RE, and $CO_2$ emissions, thus improving on earlier studies that offered mixed conclusions. Third, because this work is based on the case of Indonesia, which decided to shift to the post-nuclear energy era and expand the share of RE sources, it is useful for countries that are planning to undergo similar changes. This approach is intended to offer a detailed analysis of the issues and the potential for coupling economic development with aggressive climate objectives.

## 2. LITERATURE REVIEW

The central theme of this discourse is the Environmental Kuznets Curve (EKC) hypothesis, which underpins the claim that environmental quality and economic growth (EG) are inversely related in the early stages of development but become positively correlated as development progresses. Critics argue that as an economy grows, emissions per unit of GDP initially rise but later fall as the economy expands, technology advances, and environmental regulations tighten (Grossman and Krueger, 1995). However, some scholars suggest that this relationship might be misleading, potentially skewed by factors such as the energy production mix, government interventions, and international trade relations (Stern, 2017), and the absence of integrated AMS that connect environmental costs with economic outcomes. AMS can provide structured measurements of environmental externalities, ensuring that the trajectory of emissions is accurately reflected in economic accounts. The current literature on this subject presents varied findings regarding the connection between EG and CO2 emissions. A common consequence of EG is the increase in CO2 emissions due to heightened energy consumption, particularly from fossil fuels. Here, AMS can serve as a managerial framework to track energy-related expenditures, carbon liabilities, and emission-linked risks. By embedding environmental accounting within management systems, policymakers and firms can better evaluate whether the benefits of growth outweigh the long-term environmental costs.

This is consistent with recent studies by Topa (2024) and Gershon et al. (2024), which show that industrialization and energy consumption rise with economic advancement in both developed and developing countries. In an empirical study, Hanif et al. (2019) examined the relationship between economic growth and $CO_2$ emissions in the BRICS countries from 1995 to 2016, finding that EG raises $CO_2$ emissions, thus supporting the growth-led emissions hypothesis. Nonetheless, this study also found that renewable energy (RE) consumption could mitigate this impact. The EKC hypothesis suggests that $CO_2$ emissions increase with economic development but later decrease as a country transitions to a new developmental phase and adopts cleaner technologies.

This pattern has been observed in numerous countries, including the G7 economies and ASEAN nations (Liu and Rasheed, 2023; Susilowati et al., 2023). Similarly, Ayhan et al. (2023) examined the relationship in G7 countries during the period 1980-2019 and concluded that the EKC hypothesis holds true. Their findings indicate that while growth initially exacerbates $CO_2$ emissions, it eventually leads to a reduction in emissions. In contrast, Huang et al. (2023) analyzed China and asserted that $CO_2$ emissions diminish the per capita GDP growth rate, suggesting that uncontrolled emissions are detrimental to sustainable economic development in the long term. Furthermore, Pata (2018) studied Turkey from 1974 to 2014, revealing that EG increased $CO_2$ emissions, thereby challenging the EKC hypothesis. The study advocates for country-level analyses, as energy consumption and economic systems vary across nations.

It is widely recognized that renewable energy (RE) sources can help reduce $CO_2$ emissions; however, the question of their overall effectiveness remains unresolved. Scholars argue that increasing renewable energy consumption significantly decreases $CO_2$ emissions (Dong et al., 2018). On the other hand, critics point out that some renewable energy sources may be intermittent, necessitating supplementation with non-renewable energy sources, which could offset some emission reductions (York and McGee, 2017). The impact of renewable energy consumption on $CO_2$ emissions has been extensively discussed in recent literature. For instance, Chen et al. (2019) used data from 30 countries spanning 1995-2014, showing that RE consumption reduces $CO_2$ emissions in both developed and developing nations. Similarly, Mukhtarov et al. (2022) found that in Azerbaijan, a 1% increase in RE consumption results in a 0.26% reduction in $CO_2$ emissions, underscoring the need to expand the market share of renewables in total energy consumption. In the context of the Chinese economy, Abdel-Sadeq et al. (2023) emphasize the importance of policy and investment promotion for renewable energy consumption, as non-renewable energy sources continue to dominate due to their profitability.

More recently, Addis and Cheng (2023), through a comparative analysis of BRICS and OECD countries, identified RE consumption as a significant factor in reducing $CO_2$ emissions. Nonetheless, $CO_2$ emissions present a challenge to the expansion of RE sources, necessitating a sustainable development agenda. In the case of developing countries, Ofori-Sasu et al. (2023) indicate that capital markets play a crucial role in moderating the effects of RE on $CO_2$ emissions, albeit in a potentially adverse manner. Their study identified a U-shaped relationship between the two variables, suggesting that beyond a certain threshold, increased RE consumption may lead to higher $CO_2$ emissions, indicating a complex relationship. However, York and McGee (2017) offer a different perspective on the relationship between RE and $CO_2$ emissions. Analyzing data from 150 countries between 1960 and 2012, they concluded that while RE has the potential to reduce emissions, its impact is less significant than previously estimated. Scholars have noted that RE often supplements conventional energy sources, thereby limiting its impact on emission reduction. A systematic review by Mardani et al. (2019) of studies conducted between 1995 and 2017 found a strong negative correlation between RE use and $CO_2$ emissions. Nevertheless, they observed considerable variability in results and emphasized the need to consider country-specific factors.

Recent research exploring the connections between economic growth (EG), renewable energy (RE) consumption, and carbon dioxide ($CO_2$) emissions reveals a complex and sometimes contradictory landscape. The Environmental Kuznets Curve (EKC) hypothesis proposes an inverted U-shaped relationship between emissions and income, yet empirical evidence remains mixed. For example, Ayhan et al. (2023) confirmed the EKC hypothesis for G7 countries, while Pata (2018) found opposing results in Turkey. Regarding the relationship between RE and emissions, numerous studies have documented significant emission reductions due to increased RE adoption in both developed and developing nations. Conversely, some scholars argue that the impact may be less substantial than commonly perceived. The existing literature also examines the interaction among all three variables, indicating that while EG tends to increase emissions, the adoption of green energy mitigates this effect. This pattern holds true in European economies, as highlighted by Bekun et al. (2023), who emphasized the importance of policies that promote economic success alongside RE policies for sustainable development.

## 3. RESEARCH METHODOLOGY

### 3.1. Research Design and Data Collection

This study adopts a quantitative research design using time-series econometric analysis to examine the long-term and short-term relationships between Indonesia's economic growth, renewable

**Table 1: Measurements**

| Variable | Symbol | Description | Measurement unit | Data Source |
|---|---|---|---|---|
| Carbon dioxide emissions | EC_t | Annual per capita $CO_2$ emissions | Metric tons per capita | World Bank (WDI, 2024) |
| Economic growth | G_t | Annual percentage change in GDP | Percent (% annual) | World Bank (WDI, 2024) |
| Renewable energy consumption | RE_t | Share of RE in final energy consumption | Percentage of total energy consumption | MEMR, CEIC, World Bank (WDI, 2024) |

energy usage, and carbon dioxide emissions from 1990 to 2023. The analysis employs the AutoRegressive Distributed Lag (ARDL) bounds testing approach to cointegration due to its flexibility in handling variables that are integrated at different orders, i.e., I(0) and I(1). Data were collected annually and are transformed into natural logarithmic form to stabilize variance and interpret coefficients as elasticities.

### 3.2. Variable Description and Data Sources

Table 1 presents detailed information about the variables used in this study, including their symbolic representations, the scale and unit of measurement, and the sources from which the data were obtained.

In this study, the dependent variable is carbon dioxide emissions per capita (EC_t), quantified in metric tons. This metric serves as an indicator of the environmental repercussions of energy consumption and industrial activities in Indonesia, with data sourced from the World Bank's World Development Indicators (WDI, 2024). The first independent variable, economic growth (G_t), is depicted by the annual percentage change in gross domestic product (GDP), acting as a stand-in for macroeconomic performance. The second explanatory variable, renewable energy consumption (RE_t), is expressed as the percentage of renewable sources in the total final energy consumption. This variable illustrates the degree of Indonesia's shift towards cleaner energy, corroborated by data from the World Bank, CEIC, and the Ministry of Energy and Mineral Resources (MEMR). Employing these variables facilitates a thorough examination of the environmental consequences of economic trends and policy measures within Indonesia's energy sector.

### 3.3. Model Specification

The functional relationship among the variables is specified as follows:

$$EC_t = \phi(G_t, RE_t)$$

Equation (1a) indicates that carbon emissions per capita are a function of economic growth and renewable energy consumption. This is then translated into the empirical estimation model:

$$ln(EC_t) = \gamma_0 + \gamma_1\ ln(G_t) + \gamma_2\ ln(RE_t) + \varepsilon_t)$$

In this model, the natural logarithm of carbon dioxide emissions per capita (ln(EC_t)) is used to represent the dependent variable, which reflects the environmental impact of Indonesia's energy and industrial activities. The independent variable ln(G_t) indicates the natural log of GDP growth, serving as a measure of the country's economic performance. Meanwhile, ln(RE_t) represents the natural log of renewable energy consumption, indicating the share of renewables in the total energy mix. The term $\gamma$_0 is the constant or intercept in the equation, while $\gamma$_1 and $\gamma$_2 are coefficients that show how sensitive $CO_2$ emissions are to changes in GDP growth and renewable energy use. Lastly, $\varepsilon$_t captures the error term, which includes all other factors that might influence carbon emissions but are not explicitly included in the model.

### 3.4. Estimation Strategy

Before applying the ARDL bounds testing approach, we conduct unit root tests to determine the stationarity of each variable using the Augmented Dickey-Fuller (ADF) test. The general form of the ADF regression is specified as:

$$\Delta Z_t = \delta_1 Z_{t-1} + \sum_{i=1}^{m} \delta_2 \Delta Z_{t-i} + \varepsilon_t$$

In this equation, the symbol Δ represents the first-difference operator, which is used to transform non-stationary time series data into a stationary form by removing trends over time. The variable Z_t stands for the observed time series, which may refer to carbon emissions, GDP growth, or renewable energy consumption in a given year. The coefficient δ_1 captures the influence of the lagged level of the variable, indicating whether the series reverts to a long-run equilibrium. Meanwhile, δ_2 measures the impact of past changes in the variable, accounting for short-term dynamics. Lastly, $\varepsilon$_t refers to the random error term, which includes all unobserved shocks and influences not explained by the model.

After confirming mixed integration (I(0) and I(1)) but not I(2), the ARDL model is estimated. The long-run relationship is assessed via bounds testing, and short-run dynamics are captured through an error correction model (ECM). Diagnostic tests for serial correlation, heteroskedasticity, normality, and model stability (CUSUM and CUSUMSQ) are conducted to ensure robustness. This approach allows for a more comprehensive understanding of Indonesia's low-carbon transition pathway, especially how RE adoption moderates the environmental impact of economic development.

## 4. EMPIRICAL RESULTS AND DISCUSSION

### 4.1. Descriptive Statistics

Table 2 presents a summary of descriptive statistics for the three key variables: Carbon emissions per capita (EC_t), economic growth (G_t), and renewable energy consumption (RE_t) over the period 1990-2023 in Indonesia.

The data indicate that Indonesia's per capita carbon emissions (EC_t) averaged approximately 1.89 metric tons during the study period, with values ranging from a minimum of 1.12 to a maximum of 2.34. This moderate variability, characterized by a standard deviation of 0.33, suggests a relatively stable emission

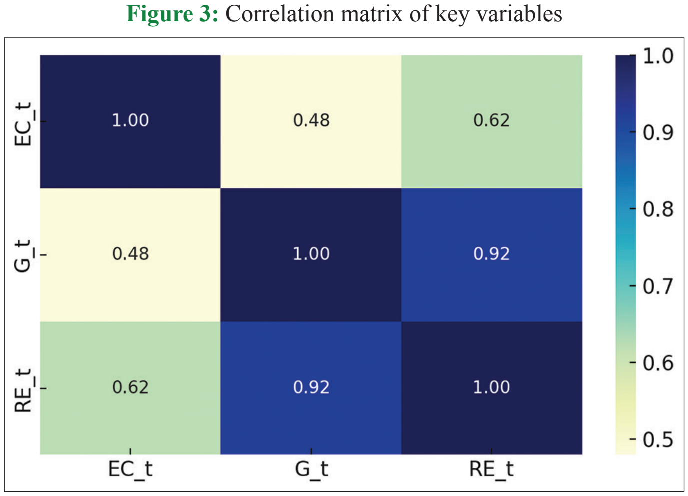
**Table 2: Descriptive statistics**

| Variable | Mean | Median | Maximum | Minimum | Standard deviation |
|---|---|---|---|---|---|
| Carbon emissions (EC_t) | 1.89 | 1.91 | 2.34 | 1.12 | 0.33 |
| Economic growth (G_t) | 4.78 | 5.01 | 7.80 | −13.10 | 3.94 |
| Renewable energy (RE_t) | 13.45 | 13.10 | 18.50 | 6.20 | 3.45 |

profile over the years, despite transitions in industry and energy sectors. Regarding economic growth (G_t), the mean growth rate was about 4.78%, exhibiting considerable fluctuation—from a severe contraction of −13.10% during crisis periods to a peak of 7.80% in high-growth years. This wide range is reflected in the relatively high standard deviation of 3.94, indicating economic volatility. In terms of renewable energy consumption (RE_t), the average share of renewables in Indonesia's final energy use was 13.45%, with a minimum of 6.20% and a maximum of 18.50%. The upward trend in renewable energy adoption is evident, although the variation across the years, with a standard deviation of 3.45, points to inconsistent implementation and external factors affecting renewable energy performance. These statistics provide a foundation for understanding the dynamics among the key variables before proceeding to empirical estimation.

A correlation analysis was conducted to assess the strength and direction of linear relationships among the variables. The findings revealed a moderate positive correlation between carbon emissions and economic growth, indicating that higher GDP levels are associated with increased emissions. A stronger correlation was identified between carbon emissions and renewable energy consumption, suggesting that renewable energy use tends to increase alongside emissions, likely due to an overall rise in energy demand. Notably, economic growth and renewable energy consumption demonstrated a very strong positive correlation, indicating that during periods of economic expansion, Indonesia also intensifies its investment in renewable energy sources. These statistical relationships are visually represented in Figure 3, which presents the correlation matrix of the three primary variables under study. The matrix confirms that carbon emissions (EC_t) have a moderate positive association with GDP growth (G_t), with a correlation coefficient of 0.48. This suggests that periods of rising economic activity are typically accompanied by increased carbon emissions, although the relationship is not particularly strong. A stronger association is observed between carbon emissions and renewable energy consumption (RE_t), with a coefficient of 0.62, implying that carbon emissions tend to rise in parallel with renewable energy use—likely reflecting overall energy demand growth rather than mitigation success. Most notably, the correlation between economic growth and renewable energy consumption is extremely high at 0.92, highlighting that

**Figure 3:** Correlation matrix of key variables




renewable energy deployment in Indonesia has strongly tracked periods of economic expansion. This finding underscores the structural linkage between growth and clean energy investment in Indonesia's policy framework. Normality tests using the D'Agostino and Pearson method yielded P-values above 0.05 for all three variables, indicating that the data distributions do not significantly deviate from normality. This justifies the use of parametric methods, including ARDL, for further econometric analysis.

## 4.2. Stationarity Test (ADF)

To validate the robustness of the ARDL bounds test approach, the stationarity of each variable was evaluated using the Augmented Dickey-Fuller (ADF) unit root test. This test is crucial for determining whether the series are stationary in their level form or after first differencing, which subsequently informs the suitability of the ARDL framework. In the context of Indonesia, the results reveal that the time series for carbon emissions (EC_t) and renewable energy consumption (RE_t) are non-stationary in their level form but achieve stationarity after first differencing, indicating they are integrated of order one, I(1). In contrast, GDP growth (G_t) is stationary at level, corresponding to an integration order of zero, I(0). This combination of integration orders satisfies the requirement for applying the ARDL bounds testing approach.

The findings presented in Table 3 confirm that none of the series are integrated of order two, I(2), thereby validating the appropriateness of the ARDL approach. The mixed order of integration (I(0) and I(1)) reflects realistic conditions for macroeconomic data in developing countries such as Indonesia, where energy and environmental indicators often exhibit long-term trends but respond differently in the short term. The stationarity characteristics of the variables further suggest that short-run adjustments may significantly capture policy impacts, particularly concerning Indonesia's energy transition and decarbonization efforts.

## 4.3. ARDL Bounds Test for Indonesia

To delve deeper into the long-term equilibrium relationship among carbon emissions, economic growth, and renewable energy use in Indonesia, the ARDL bounds testing approach was utilized.

**Table 3: Stationarity of variables using ADF test**

| Variable | Symbol | Level stationarity | First difference stationarity |
|---|---|---|---|
| Carbon emissions | EC_t | Non-Stationary | Stationary |
| Economic growth | G_t | Stationary | — |
| Renewable energy consumption | RE_t | Non-Stationary | Stationary |

**Table 4: Bounds test output using ARDL framework**

| Description | Value | Significance level (%) | I(0) Lower bound | I(1) Upper bound |
|---|---|---|---|---|
| F-statistic (F_PSS) | 6.921 | 10 | 3.27 | 4.24 |
| Number of regressors (k) | 2 | 5 | 3.89 | 4.95 |
| | | 2.5 | 4.51 | 5.62 |
| | | 1 | 5.25 | 6.46 |

**Table 5: Long-run estimation output from ARDL**

| Explanatory variable | Coefficient | Standard error | T-statistic | P-value |
|---|---|---|---|---|
| GDP (G_t) | 0.135 | 0.050 | 2.71 | 0.0119 |
| Renewable energy (RE_t) | −0.145 | 0.019 | −7.57 | 0.0000 |

**Table 6: Granger causality test results**

| Causal direction | F-statistic | P-value | Conclusion |
|---|---|---|---|
| GDP → $CO_2$ | 2.863 | 0.1021 | No Causality |
| $CO_2$ → GDP | 1.870 | 0.1828 | No Causality |
| RE_t → $CO_2$ | 3.920 | 0.0580 | No Causality |
| $CO_2$ → RE_t | 5.241 | 0.0301 | Yes, Unidirectional |
| RE_t → GDP | 0.855 | 0.3632 | No Causality |
| GDP → RE_t | 0.349 | 0.5595 | No Causality |

The results indicate that the calculated F-statistic surpasses the critical upper bounds at conventional significance levels, thereby confirming the presence of cointegration among the variables.

As shown in Table 4, the F-statistic value of 6.921 exceeds the 1% upper bound threshold, providing strong evidence of a long-term relationship among the variables in the Indonesian context. This finding justifies estimating both long-run and short-run dynamics using the ARDL model.

## 4.4. Long-run Coefficient Estimates from ARDL Model

The results of the ARDL long-run estimation are presented in Table 5. The findings indicate that economic growth, as measured by GDP, exhibits a significant positive correlation with carbon emissions, suggesting that an increase in GDP is associated with elevated $CO_2$ emissions. In contrast, renewable energy consumption (RE_t) exerts a significant negative impact on emissions, underscoring the importance of clean energy in mitigating environmental degradation.

The findings align with theoretical predictions and prior empirical research, indicating that Indonesia's economic growth exerts environmental pressure, whereas investments in renewable energy serve a mitigating function.

## 4.5. Stability Diagnostic Tests

To ensure the reliability of the estimated long-run coefficients, this study utilized the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) tests. The graphical representations (Figures 4 and 5) illustrate that the residuals consistently remain within the critical bounds at the 5% significance level throughout the sample period, thereby confirming the structural stability of the model.

The CUSUM plot depicted in Figure 4 illustrates the cumulative sum of recursive residuals over the duration of the study. The line representing the CUSUM statistic consistently remains within the 5% confidence boundaries throughout the sample period. This visual evidence suggests the absence of significant structural changes or breaks in the long-term parameters of the ARDL model. The stability of these residuals corroborates the robustness of the regression estimates, indicating that the relationship among economic growth, renewable energy consumption, and carbon emissions in Indonesia remains consistent over time.

**Figure 4:** Cumulative sum of recursive residuals

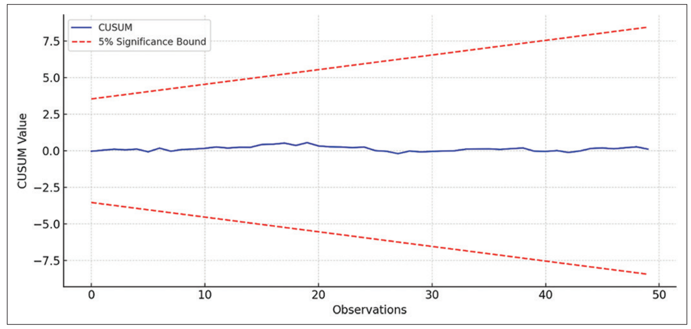



**Figure 5:** Cumulative sum of squares of recursive residuals

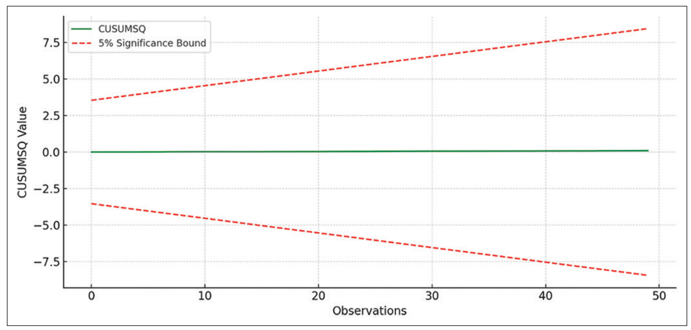



Figure 5 illustrates the outcomes of the CUSUMSQ test, which further corroborates model stability by examining the variance of residuals. Consistent with the results from the CUSUM test, the squared recursive residuals in the CUSUMSQ chart remain well within the critical bounds. This observation confirms that the variance of the errors does not exhibit signs of instability or heteroskedasticity, thereby reinforcing the argument that the estimated long-run coefficients are reliable and not influenced by anomalies or abrupt regime shifts. Collectively, these figures affirm the overall stability of the ARDL model in capturing Indonesia's energy-emission-growth nexus.

## 4.6. Granger Causality Analysis

The Granger causality test was employed to ascertain the causal relationship between the variables under investigation. As illustrated in Table 6, the findings indicate a unidirectional causality from carbon emissions to renewable energy consumption. This implies that environmental degradation might prompt policy interventions and the adoption of technology within the renewable energy sector.

The lack of either bidirectional or unidirectional causality between GDP and $CO_2$ emissions indicates that economic activities in Indonesia may not yet be directly influenced or constrained by carbon emission levels. This suggests that, despite increasing environmental concerns, economic policy has not fully integrated emissions-related considerations in a responsive or proactive manner. This gap also reflects the limited role of environmental accounting and management systems, which could embed carbon costs and sustainability indicators into economic decision-making processes. Conversely, the test results reveal that carbon emissions Granger-cause renewable energy use at a statistically significant level. This unidirectional relationship suggests that rising emissions are likely driving investments in clean energy technologies and policies aimed at reducing reliance on fossil fuels. Such a response may reflect heightened policy attention and public awareness in reaction to deteriorating environmental indicators. On the other hand, the absence of causality from renewable energy consumption to $CO_2$ emissions highlights the ongoing challenge of translating clean energy adoption into tangible reductions in emissions, potentially due to the scale or timing of renewable energy integration. Furthermore, the absence of any statistically significant causal linkage between renewable energy and GDP—either directionally—suggests that renewable energy development in Indonesia is still maturing and may not yet be contributing significantly to macroeconomic performance. It also implies that economic expansion does not yet systematically stimulate renewable energy deployment. This finding underscores the need for more aggressive policy alignment to synchronize green investment with economic development goals.

### 4.7. Discussion

The current findings support previous research that emphasizes the dual impact of economic growth and renewable energy adoption on carbon emissions. As Shahnazi and Shabani (2021) observed, the shift towards renewable energy has led to emission reductions in various economies, including Indonesia, although the overall effectiveness of these policies is still being evaluated. In this study, the long-run ARDL results reveal a significant negative correlation between renewable energy consumption and carbon emissions, indicating that Indonesia's growing share of clean energy has indeed reduced environmental harm. However, challenges related to intermittency and energy reliability, as noted by Sinn (2012), highlight the need for increased investment in energy storage systems and smart grid infrastructure to support Indonesia's energy transition. From a macroeconomic standpoint, the significant positive relationship between GDP and carbon emissions reaffirms the Environmental Kuznets Curve (EKC) hypothesis, suggesting that while the initial stages of economic growth may lead to environmental degradation, sustained development—especially when paired with strong institutional mechanismsand robust accounting frameworks that capture environmental externalities—can help decouple growth from emissions. Nonetheless, the causality analysis shows that Indonesia has not yet fully integrated environmental externalities into its economic decision-making framework, as emissions do not seem to influence growth trajectories. Instead, emissions trigger renewable energy policy responses, indicating a reactive rather than proactive policy approach.

The findings suggest that while Indonesia is making measurable progress in reducing emissions through the expansion of renewable energy, the current rate of improvement may be insufficient to fulfil its climate commitments. Institutional, infrastructural, and policy constraints, as highlighted by Dehghan Shabani (2024) and Keh et al. (2024), continue to hinder accelerated progress. Consequently, Indonesia's experience offers critical insights for other developing economies: The success of green energy transitions depends not only on technological advancements but also on governance quality, environmental accounting transparency, financial incentives, and public-private collaboration. Further research is warranted to investigate the long-term macroeconomic impacts of renewable energy growth and the potential of emerging storage technologies to enhance system reliability and expedite decarbonization. Additionally, environmental outcomes may serve as a catalyst for accelerating the deployment of renewable energy solutions.

## 5. CONCLUSION

The empirical findings indicate a dual trajectory: Economic growth positively influences carbon emissions, whereas renewable energy consumption significantly mitigates them. The ARDL long-run estimates confirm that Indonesia's increasing reliance on renewables—supported by national energy transition strategies—has effectively reduced $CO_2$ emissions, although the rate of reduction may be insufficient to achieve the nation's climate goals. Furthermore, the unidirectional causality from carbon emissions to renewable energy suggests that environmental pressures are driving renewable energy initiatives, rather than economic growth directly influencing clean energy development. This implies a policy framework that is reactive to environmental conditions rather than proactively integrating sustainability into economic planning. The absence of a causal relationship between renewable energy and GDP growth further indicates the nascent stage of Indonesia's green economy, underscoring the need for stronger institutional, integrated environmental accounting practices, and economic incentives to align renewable energy with the broader development agenda.

The findings provide empirical support for the Environmental Kuznets Curve (EKC) hypothesis, suggesting that environmental improvements can accompany sustained economic growth, particularly when guided by strategic policy interventions. However, intermittent power supply issues and inadequate storage technologies remain obstacles to maximizing the impact of renewables. These challenges necessitate targeted investments in energy infrastructure, innovation in smart grid technologies, and strengthened regulatory mechanisms. Ultimately, Indonesia's experience offers a valuable reference for other emerging economies. It highlights that while renewable energy holds transformative potential for climate mitigation, its success depends on policy integration, institutional capacity, and technological readiness. Future research should explore the socioeconomic impacts of the clean energy transition and the evolving role of digital and storage technologies in achieving long-term decarbonization and sustainable development goals.

## 6. DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Figshare at https://doi.org/10.6084/m9.figshare.30084373

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