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A Deep Dive into Indonesia's CO_2 Emissions: The Role of Energy Consumption, Economic Growth and Natural Disasters

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Abstract

This study examines the influence of non-renewable energy consumption, renewable energy consumption, economic growth, and natural disasters on Indonesia's carbon dioxide (CO_2) emissions spanning from 1980 to 2021. The Autoregressive Distributed Lag (ARDL) model is employed, with supplementary robustness checks utilizing Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegration Regression (CCR). The findings reveal that economic growth, along with non-renewable and renewable energy consumption, significantly affects CO_2 emissions in both the short and long term. Robustness checks confirm the positive impact of non-renewable energy consumption and economic growth, while renewable energy consumption has a negative effect on CO_2 emissions. Moreover, natural disasters exhibit a positive short-term impact on CO_2 emissions. Pairwise Granger causality results further underscore the intricate relationships between the variables. To mitigate climate change and curb CO_2 emissions in Indonesia, the study recommends implementing policies that foster sustainable economic development, encourage the adoption of renewable energy, and enhance disaster resilience.

1. Introduction

Climate change is one of the most pressing issues facing the world today [1–4]. The increase in CO_2 emissions is a major contributor to this problem [5, 6]. Indonesia, as one of the largest emitters of CO_2 in the world, has a significant role to play in addressing this issue [7, 8]. The country's reliance on non-renewable energy sources has contributed to its high levels of CO_2 emissions [9]. At the same time, Indonesia has made significant strides in developing renewable energy sources, such as biomass, geothermal, and hydroelectric power [10–12]. The country's economic growth and natural disasters have also had an impact on its CO_2 emissions [13].

Non-renewable energy consumption, primarily of coal, oil, and natural gas, has been the backbone of Indonesia's economic growth [14–16]. However, previous studies indicate that the use of non-renewable energy and its consumption are significant factors contributing to the increase in CO_2 emissions globally [17–19]. The combustion of fossil fuels releases large quantities of CO_2 emissions, exacerbating the global issue of climate change [20–22]. In Indonesia, the dependence on these energy consumptions has led to increased CO_2 emissions, posing challenges to environmental sustainability. Understanding the scope and characteristics of these CO_2 emissions is vital for formulating strategies to mitigate their impact [23–25].

In contrast, renewable energy consumption, sourced from hydro, solar, wind, biomass, and geothermal power, offers a more sustainable alternative with lower CO_2 emissions [26, 27]. Indonesia's geographical diversity presents vast potential for renewable energy development [10, 11, 28]. The adoption of these cleaner energy consumption is pivotal in reducing the country's carbon footprint. As a result, this shift not only contributes to a more sustainable environment but also aligns with global efforts to combat climate change. Numerous studies, have highlighted the decrease in CO_2 emissions resulting from a shift to renewable energy [29–35]. Given the widespread concern over greenhouse gases, it's anticipated that CO_2 emissions will indirectly but significantly impact the adoption of renewable energy consumption.

Economic growth in Indonesia is closely linked to energy consumption and, consequently, CO_2 emissions [36]. As the economy expands, the demand for energy rises, often met by burning more fossil fuels [37]. This growth-driven increase in CO_2 emissions poses a challenge to sustainable development. The country faces the dual task of fueling its economic expansion while mitigating environmental impacts [38]. The relationship between economic growth and CO_2 emissions has been extensively examined through empirical research. Studies employing diverse countries, variables, and methodological approaches have provided robust evidence of this association. A series of studies conducted across different countries have consistently demonstrated a positive correlation between economic growth and CO_2 emissions. Employing advanced econometric methods like ARDL, FMOLS, and DOLS, these studies have analyzed data from various periods, ranging from the 1970s to the 2010s. Key findings from countries including Pakistan [39], China [40], Kazakhstan [41], Indonesia [42], Turkey [43], Nigeria [44], South Africa [45], Egypt [46], Bangladesh [47], and India [48]. These studies collectively underscore the environmental challenges associated with economic development, highlighting a consistent increase in CO_2 emissions as economies expand.

Furthermore, natural disasters, common in Indonesia due to its geographic location [49], also play a role in CO_2 emissions [13, 50]. Events such as volcanic eruptions can release significant amounts of CO_2 emissions, while disasters like floods and earthquakes can disrupt energy infrastructure, leading to increased reliance on fossil fuels for emergency power [51, 52]. Few studies have examined the relationship between natural disasters and CO_2 emissions [13]. However, prevailing hypotheses propose an inverse association, attributable to the interconnections between economic activity and energy consumption. This supposition argues disasters reduce economic activity and energy consumption, thereby decreasing CO_2 emissions [53–56]. Analyzing 138 countries revealed that disasters substantially lower CO_2 emissions by directly and indirectly reducing energy consumption, where technological progress strongly influences this trend [57]. Nevertheless, the precise mechanisms linking disasters and CO_2 emissions remain unclear. A prominent hypothesis states disasters cause poverty, curtailing energy consumption and CO_2 emissions [58, 59].

However, various factors, including democracy, political variables, and human development, influence the efficacy of environmental policies in reducing CO_2 emissions. Notably, cryptocurrency mining significantly increases emissions due to its high energy consumption. Additionally, the performance of a company's stock plays a pivotal role in guiding its investments in green technologies, significantly shaping the broader trend of CO_2 emissions [60–66].

This study provided an in-depth exploration of the complex impact of non-renewable and renewable energy consumption, economic growth, and natural disasters on CO_2 emissions in Indonesia. As Indonesia continues to navigate the path of economic development, this research offers valuable insights into how it can balance this growth with environmental sustainability. The study highlights the need for strategic policy interventions and a shift towards renewable energy consumption to mitigate the adverse effects of CO_2 emissions, ensuring a more sustainable future for Indonesia.

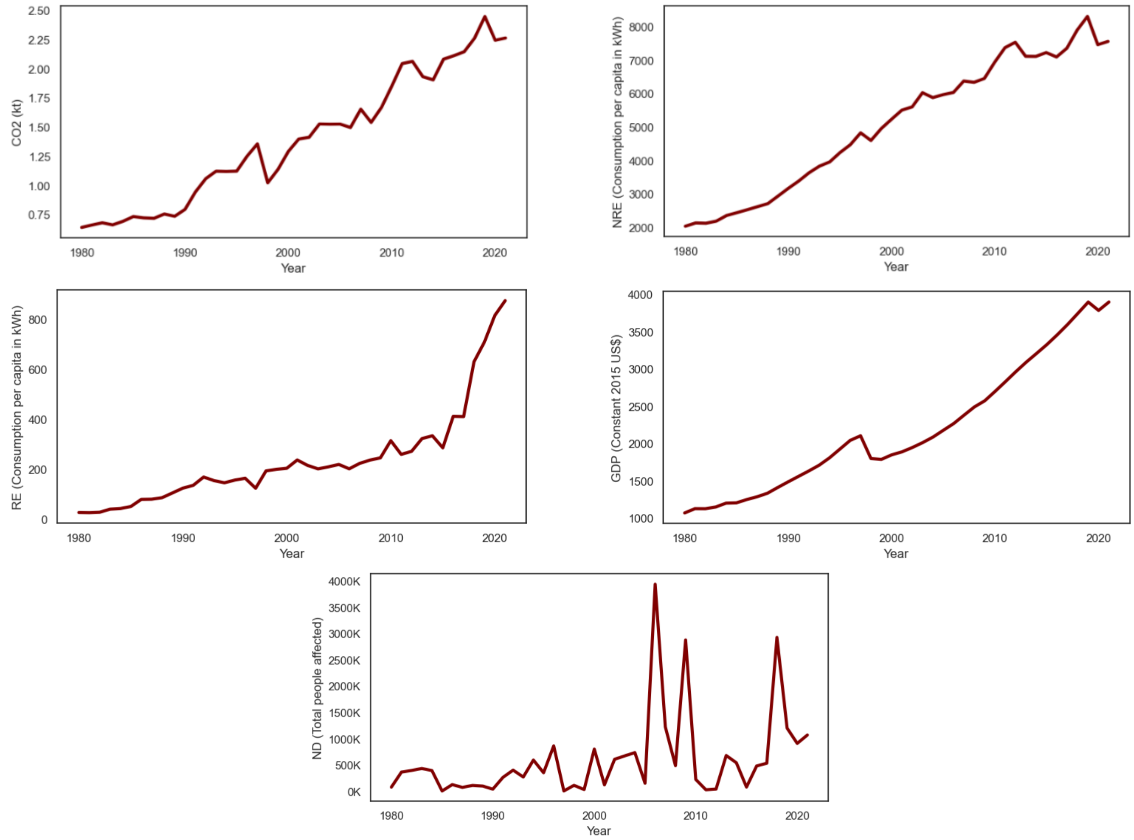

Figure 1. Trends of the variables.

2. Materials and Methods

2.1. Data

This study utilizes annual data from Indonesia covering the period from 1980 to 2021. Data on CO_2 emissions (CO_2) and economic growth (GDP) were obtained from the World Development Indicators (WDI) of the World Bank. Additionally, data on non-renewable consumption (NRE) and renewable energy consumption (RE), as well as natural disasters (ND), was sourced from OurWorldInData (OWID). Table 1 presents a detailed summary of the variables, and Figure 1 illustrates the trends in CO_2, GDP, NRE, RE, and ND over time. To mitigate potential heteroscedasticity, all data were transformed into natural logarithms.

2.2. Empirical model

This study employs an empirical model adapted from previous works [67, 68] to examine the relationship among CO_2 emissions, non-renewable energy consumption, renewable energy consumption, economic growth, and natural disasters. To achieve this aim, the initial function is presented as Equation 1.

$$CO2_t = f\,(NRE_t, RE_t, GDP_t, ND_t) \qquad (1)$$

Where $CO2_t$ is the CO_2 emissions at time t, NRE_t is the non-renewable energy consumption at time t, RE_t is renewable energy consumption at time t, GDP_t is economic growth at time t, and ND_t is natural disasters at time t. The economic model is represented by the Equation 2.

$$CO2_t = \beta_0 + \beta_1 NRE_t + \beta_2 RE_t + \beta_3 GDP_t + \beta_4 ND_t \qquad (2)$$

Additionally, equation 2 can be expanded into Equation 3, representing the econometric model.

$$CO2_t = \beta_0 + \beta_1 NRE_t + \beta_2 RE_t + \beta_3 GDP_t + \beta_4 ND_t + \varepsilon_t \qquad (3)$$

Where β_0 is the intercept and ε_t the error term, while $\beta_1 - \beta_4$ signify the respective coefficients. Furthermore, we have transformed equation 3 into logarithmic form for time series analysis in Equation 4.

$$lnCO2_t = \beta_0 + \beta_1 lnNRE_t + \beta_2 lnRE_t + \beta_3 lnGDP_t + \beta_4 lnND_t + \varepsilon_t \qquad (4)$$

Where $lnCO2$, $lnNRE_t$, $lnRE_t$, $lnGDP_t$, and $lnND_t$ represent the logarithmic forms of CO_2 emissions, non-renewable energy consumption, renewable energy consumption, economic growth and natural disasters at time t, respectively.

Table 1. Variable descriptions.

Variable	Logarithms	Objectives	Unit	Source
Carbon dioxide emissions (CO_2)	lnCO2	To measure the impact of human activities on climate change, as CO_2 is a major greenhouse gas.	Kilotons (kt)	WDI
Nonrenewable energy consumption (NRE)	lnNRE	To understand the consumption patterns of energy sources that cannot be replenished, such as coal, oil, and natural gas.	Per capita in kilowatt-hours equivalent (kWh)	OWID
Renewable energy consumption (RE)	lnRE	To assess the use of energy sources that can be regenerated, like solar, wind, and hydro power, and their role in sustainable energy transition.	Per capita in kilowatt-hours equivalent (kWh)	OWID
Economic growth per capita (GDP)	lnGDP	To show the average rise in prosperity for each individual in a country's economy	Constant 2015 US$	WDI
Natural disasters (ND)	lnND	To measure the number of individuals impacted by naturally occurring catastrophes such as hurricanes, earthquakes, and floods.	Number of total people affected	OWID

2.3. Estimation techniques

2.3.1. Autoregressive Distributed Lag (ARDL)

The ARDL model, an econometric approach for analyzing long-term relationships between economic variables, outperforms other techniques. By estimating both long and short-term effects, excelling with small sample sizes, and effectively addressing autocorrelation issues, the ARDL model offers a robust statistical method for modeling connections among economic time series data. The ARDL approach stands as a valuable tool in understanding the intricate dynamics of economic variables, represented by equation 5.

$$\begin{aligned}\Delta lnCO2_t = \beta_0 + \textstyle\sum_{i=1}^{q} \beta_1 \Delta lnCO2_{t-i} + \sum_{i=0}^{p} \beta_2 \Delta lnNRE_{t-i} + \sum_{i=0}^{p} \beta_3 \Delta lnRE_{t-i} + \sum_{i=0}^{p} \beta_4 \Delta lnGDP_{t-i} + \sum_{i=0}^{p} \beta_5 \Delta lnND_{t-i} + \\ \delta_1 lnCO2_{t-1} + \delta_2 lnNRE_{t-1} + \delta_3 lnRE_{t-1} + \delta_4 lnGDP_{t-1} + \delta_5 lnND_{t-1} + \varepsilon_t\end{aligned} \quad (5)$$

Where, i denotes the country and Δ is the first difference operator. The $\beta_1 - \beta_5$ coefficients represent the long-term impact, while the $\delta_1 - \delta_5$ coefficients capture short-term effects. Additonally, q and p indicate the optimum lag length.

2.3.2. Robustness check with Fully-Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS) and Canonical Cointegration Regression (CCR)

The subsequent step involves estimating the long-term parameters. Although co-integration tests ascertain the existence of a long-term relationship, they do not facilitate the exploration of long-term elasticity estimates. Therefore, it becomes imperative to examine the long-term equilibrium relationship between the variables through FMOLS, DOLS and CCR analyses. These advanced methods effectively address issues such as the serial correlation of long-term execution and endogeneity problems, thereby ensuring consistent and reliable estimates based on the selected samples.

2.3.3. Pairwise Granger causality test

The Granger causality test examines predictive relationships between time series variables [69]. It tests whether past values of one variable significantly forecast future values of another variable. Rejecting the null hypothesis that one time series does not Granger-cause the other suggests a predictive association, though not necessarily causal. Robustness checks and sensitivity analysis should be conducted to ensure reliability, given that Granger causality implies predictability rather than true causation. The flowchart in Figure 2 illustrates the stages of the process.

3. Results and Discussion

3.1. Summary of variable characteristics

The Table 2 displays log-transformed descriptive statistics for five variables that likely represent environmental and economic data. Key observations include the mean values indicating the central tendency after log transformation, with CO_2 showing a negative minimum value, hinting at original values less than 1. The standard deviations are low, suggesting limited spread around the mean, and skewness values are negative for most variables, indicating left-skewed distributions. The kurtosis values suggest relatively peaked distributions, especially for ND.

3.2. Unit root test

The unit root test was conducted to establish the appropriateness of employing the ARDL estimator for cointegration, ensuring that all variables remained within the required integration order. First, we present the outcomes of the Augmented Dickey-Fuller (ADF) [70] and

Table 2. Descriptive statistics.

Variable	lnCO2	lnNRE	lnRE	lnGDP	lnND
Mean	0.2428	8.4451	5.1337	7.6167	12.5016
Median	0.3194	8.5880	5.3014	7.5890	12.8859
Max.	0.8945	9.0243	6.7750	8.2669	15.1860
Min.	-0.4459	7.6193	3.2044	6.9728	8.5914
Std. Dev.	0.4278	0.4467	0.8819	0.3944	1.4850
Skewness	-0.2146	-0.5249	-0.4967	0.0815	-0.6909
Kurtosis	1.7218	1.8671	3.0439	1.9144	3.3848
Obs.	42	42	42	42	42

Table 3. The results of ADF and P-P unit root test.

Variable	ADF Statistical Value		P-P Statistical Value	
	Level	1st Difference	Level	1st Difference
lnCO2	0.7674	0.0000***	0.7293	0.0000***
lnGDP	0.9254	0.0002***	0.9254	0.0002***
lnNRE	0.1489	0.0000***	0.0765	0.0000***
lnRE	0.5313	0.0000***	0.6881	0.0000***
lnND	0.0002***	0.0000***	0.0003***	0.0001***

Note: ** and *** represent 5% and 1% levels of significance, respectively.

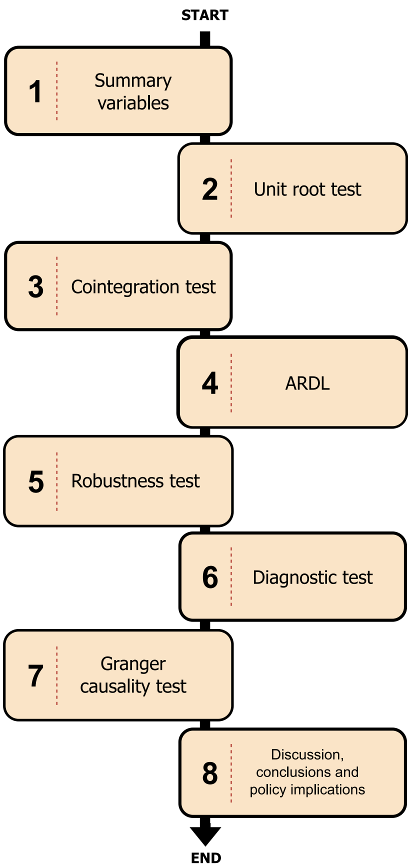

Figure 2. Flowchart analysis.

Table 4. ARDL bounds test results.

F-bounds test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	6.7010	At 10%	2.2	3.09
K	4	At 5%	2.56	3.49
		At 2.5%	2.88	3.87
		At 1%	3.29	4.37

Phillips-Perron (PP) [71] unit root tests in Table 3, where all variables are stationary at the first difference. In detail, the results from the ADF and PP unit root tests indicate that ND is stationary at the level, while CO_2, NRE, RE, and GDP are stationary at the first difference, as evidenced by their significant first differences at the 1% level. After successfully passing the unit root tests, indicating that the data series are stationary, it is essential to proceed with the cointegration test.

3.3. ARDL bound test

After confirming that all variables were stationary, we proceeded with a cointegration test using the ARDL bound test. The results, as shown in Table 4, indicate that the F-statistic of 6.71 surpasses both the upper and lower critical values at the 5% significance level. This rejects the null hypothesis of no cointegration, indicating the variables are cointegrated. The significant F-statistic points to a long-term relationship between the variables. With confirmed cointegration, the analysis can proceed using the ARDL approach to estimate both long-term and short-term effects.

3.4. Econometric results

3.4.1. Short-term estimation with ARDL

The ARDL estimation results, as shown in Table 5, reveal that all independent variables have a significant impact

Table 5. The results of ARDL, FMOLS, DOLS, and CCR estimations, along with diagnostic test outcomes.

Variable	ARDL		FMOLS		DOLS		CCR	
	Coeff.	Prob.	Coeff.	Prob.	Coeff.	Prob.	Coeff.	Prob.
Long-run								
lnNRE	0.5598*	0.0000	0.5506*	0.0000	0.5824*	0.0000	0.5453*	0.0000
lnRE	-0.0740**	0.0339	-0.0665**	0.0467	-0.0737**	0.0265	-0.0624***	0.0752
lnGDP	0.5973*	0.0000	0.5955*	0.0000	0.5834*	0.0000	0.5907*	0.0000
lnND	0.0150***	0.0715	0.0057	0.3831	0.0031	0.6448	0.0084	0.3475
C	-8.8463*	0.0000	-8.6745*	0.0000	-8.7796*	0.0000	-8.6453*	0.0000
R2	0.9924		0.9866		0.9876		0.9864	
R2 Adsjusted	0.9901		0.9852		0.9862		0.9848	
Short-run								
$\Delta lnCO2_{(-1)}$	0.5733*	0.0003						
$\Delta lnCO2_{(-2)}$	-0.4094*	0.0049						
ΔlnNRE	0.4681*	0.0000						
ΔlnRE	-0.0619***	0.0517						
ΔlnGDP	1.0227*	0.0001						
$\Delta lnGDP_{(-1)}$	-1.1862*	0.0048						
$\Delta lnGDP_{(-2)}$	0.6628**	0.0265						
ΔlnND	0.0012	0.8344						
$\Delta lnND_{(-1)}$	0.0115**	0.0310						
Diagnostic tests				**Decision**				
Jarque-Bera	2.3923	0.3024		Residuals are normally distributed				
Breusch-Godfrey LM test	0.2216	0.9889		No serial correlation exists				
Breusch-Pagan-Godfrey test	0.2431	0.7858		No heteroscedasticity exists				
Ramsey RESET test	0.3737	0.6915		The model is properly specified				

Note: *, ** and *** represent 1%, 5% and 10% level of significance.

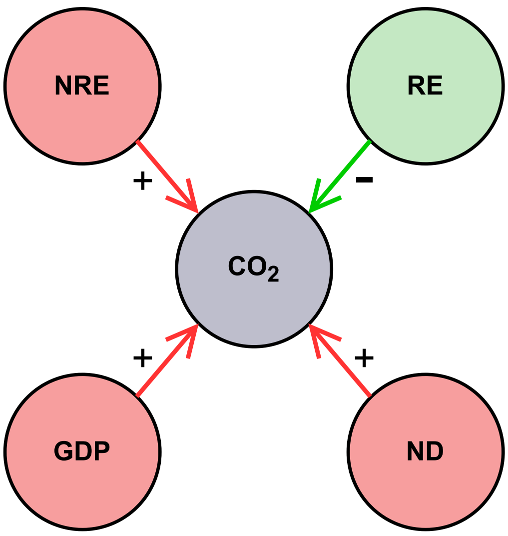

Figure 3. Overview of the long-term impact of NRE, GDP, and ND on CO_2 emissions.

on CO_2 emissions in the short term. The application of the ARDL model underscores the dynamic interactions among these variables, highlighting their collective influence on CO_2 emissions over a short-term period. The statistically significant relationships identified emphasize the importance of the chosen set of factors in this study when addressing short-term fluctuations in CO_2 emissions.

The results found that CO_2 $Lag_{(-1)}$ fosters a positive impact, whereas CO_2 $Lag_{(-2)}$ exerts a negative effect on the current CO_2 emissions. Similarly, NRE signifies a positive outcome, contrasting with the negative impact of RE on CO_2. Moreover, both GDP and GDP $Lag_{(-2)}$ contribute positively, while GDP $Lag_{(-1)}$ introduces a negative influence on CO_2. Additionally, ND $Lag_{(-1)}$ demonstrates a positive correlation with CO_2. Furthermore, with the exception of the RE variable, all independent variables exhibit a statistically strong and significant impact, as evident from probability values below 0.05. Specifically, a 1.0% increase in CO_2 $Lag_{(-1)}$ can elevate current CO_2 emissions by 0.5733%, whereas a 1.0% increase in CO_2 $Lag_{(-2)}$ can reduce current CO_2 emissions by 0.4094%. Furthermore, a 1.0% increase in NRE can raise CO_2 emissions by 0.4681%, while a 1.0% increase in RE can decrease CO_2 emissions by 0.0619%. Moreover, a 1.0% increase in both GDP and GDP $Lag_{(-2)}$ can result in a 1.0227% and 0.6628% increase in CO_2, respectively, while a 1.0% increase in GDP $Lag_{(-1)}$ can lead to a 1.1862% decrease in CO_2. Additionally, a 1.0% increase in ND $Lag_{(-1)}$ can contribute to a 0.0115% increase in CO_2 emissions.

3.4.2. Long-term estimation with ARDL, FMOLS, DOLS, and CCR

In parallel with the findings related to short-term outcomes, the ARDL model results in Table 5 also emphasize the noteworthy point that all independent variables, except ND, exert a significant and consistent impact in the same direction on the levels of CO_2

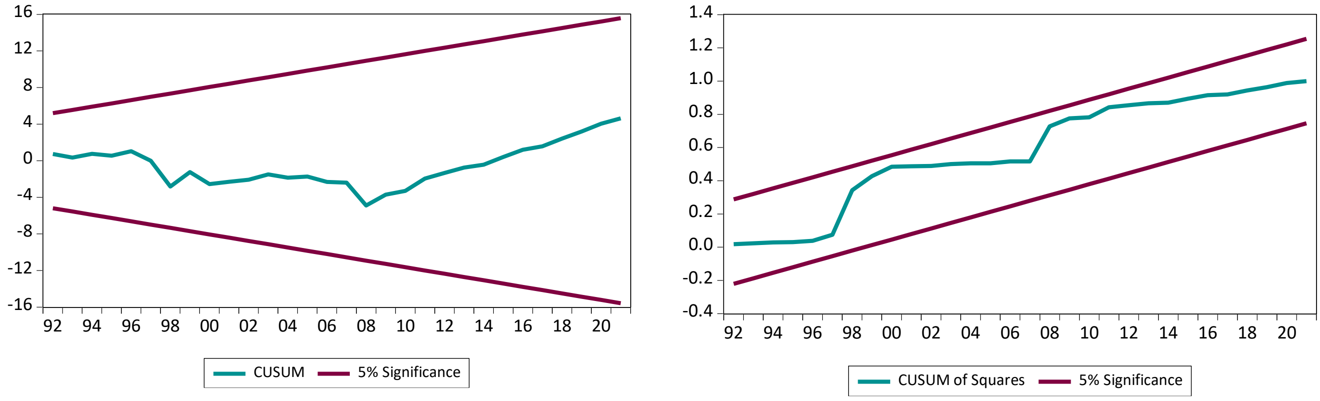

Figure 4. CUSUM and CUSUMQ test.

emissions. This includes robustness checks with FMOLS, DOLS, and CCR methods. The consistency and coherence of the identified impacts, reinforcing the understanding that each of these variables plays a pivotal role in shaping and influencing the overall levels of CO_2 over both short and long-term periods.

The results indicate that NRE implies a positive outcome, with a 1.0% increment potentially resulting in a long-term increase in CO_2 emissions by 0.5598%, 0.5506%, 0.5824%, and 0.5453% according to ARDL, FMOLS, DOLS, and CCR, respectively. Conversely, RE demonstrates an intriguing negative effect, with a 1.0% rise possibly leading to a long-term decrease in CO_2 emissions by 0.0740%, 0.0665%, 0.0737%, and 0.0624% according to ARDL, FMOLS, DOLS, and CCR, respectively. Moreover, GDP contributes positively, with a 1.0% increase potentially causing a long-term rise in CO_2 emissions by 0.5973%, 0.5955%, 0.5834%, and 0.5907% according to ARDL, FMOLS, DOLS, and CCR, respectively. Finally, ND exhibits a weak positive impact on CO_2 emissions in the long-term based on ARDL results, but these findings lack robustness according to FMOLS, DOLS, and CCR methods, with a 1.0% increase potentially resulting in a 0.0150% increase in CO_2 emissions. The overview of the long-term impact of each variable on CO_2 emissions is visualized in Figure 3.

Additionally, Table 5 presents the R-squared (R^2) and R^2 Adjusted values for the ARDL, FMOLS, DOLS, and CCR econometric models, with R^2 values spanning approximately from 0.9864 to 0.9924 and R^2 Adjusted values from around 0.9848 to 0.9901. These values confirm that the explanatory power of the models is robust to the inclusion of multiple variables, ensuring a strong model fit and high predictive accuracy.

3.4.3. Diagnostic test

The Table 5 presents the outcomes of several diagnostic tests applied to a statistical model. The Jarque-Bera test, with a coefficient of 2.3923 and a probability of 0.3024, indicates that the residuals are normally distributed, given the probability is not below the common significance threshold. Additionally, Figure 4 illustrates that the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squares of recursive residuals (CUSUMQ) tests remained within the 5% significance level critical bounds during the entire study period, indicating model stability. Thus, we can infer that both the short-term and long-term coefficients in the ARDL models are stable. The Breusch-Godfrey LM test shows a coefficient of 0.2216 and a high probability of 0.9889, suggesting the absence of serial correlation in the residuals. Similarly, the Breusch-Pagan-Godfrey test reports a coefficient of 0.2431 and a probability of 0.7858, indicating no evidence of heteroscedasticity, which implies a constant variance of errors across the model. Finally, the Ramsey RESET test with a coefficient of 0.3737 and a probability of 0.6915 confirms that the model is appropriately specified, with no omitted variables or incorrect functional form, as indicated by the probability well above conventional significance levels.

3.4.4. Pairwise Granger causality

To enhance the comprehensiveness of the empirical results, this study also utilized pairwise Granger causality analysis to identify the directions of causality among the variables, as presented in Table 6. In a concise summary, this study identified two bidirectional and four unidirectional causalities. Specifically, bidirectional causality was observed between NRE and CO_2, as well as between GDP and RE. Additionally, unidirectional causality was identified from RE to CO_2, from ND to CO_2, from ND to NRE, and from ND to GDP. The overview of these results can be seen in Figure 5.

3.5. Discussion

The presented results from various approaches shed light on the intricate dynamics influencing CO_2 emissions in Indonesia, revealing a nuanced short-term

Table 6. The results of pairwise Granger causality test.

Null Hypothesis:	F-Stat.	Prob.	Causality Direction
lnNRE ≠ lnCO2	3.41944**	0.0440	NRE ↔ CO2
lnCO2 ≠ lnNRE	2.53949***	0.0934	
lnRE ≠ lnCO2	4.27497**	0.0218	RE → CO2
lnCO2 ≠ lnRE	0.37608	0.6893	
lnGDP ≠ lnCO2	0.82200	0.4479	GDP ≠ CO2
lnCO2 ≠ lnGDP	0.52329	0.5971	
lnND ≠ lnCO2	4.08895**	0.0254	ND → CO2
lnCO2 ≠ lnND	1.72406	0.1931	
lnRE ≠ lnNRE	2.00808	0.1494	RE ≠ NRE
lnNRE ≠ lnRE	0.10595	0.8998	
lnGDP ≠ lnNRE	0.36630	0.6959	GDP ≠ NRE
lnNRE ≠ lnGDP	1.54592	0.2273	
lnND ≠ lnNRE	2.79448***	0.0748	ND → NRE
lnNRE ≠ lnND	1.87621	0.1683	
lnGDP ≠ lnRE	3.31436**	0.0481	GDP ↔ RE
lnRE ≠ lnGDP	3.57720**	0.0386	
lnND ≠ lnRE	0.91010	0.4118	ND ≠ RE
lnRE ≠ lnND	1.58802	0.2187	
lnND ≠ lnGDP	2.70379***	0.0809	ND → GDP
lnGDP ≠ lnND	1.37432	0.2663	

Note: ** and *** represent significance levels of 5% and 10%, respectively. The symbol (→) indicates unidirectional causality, (↔) indicates bidirectional causality, and (≠) indicates no causality.

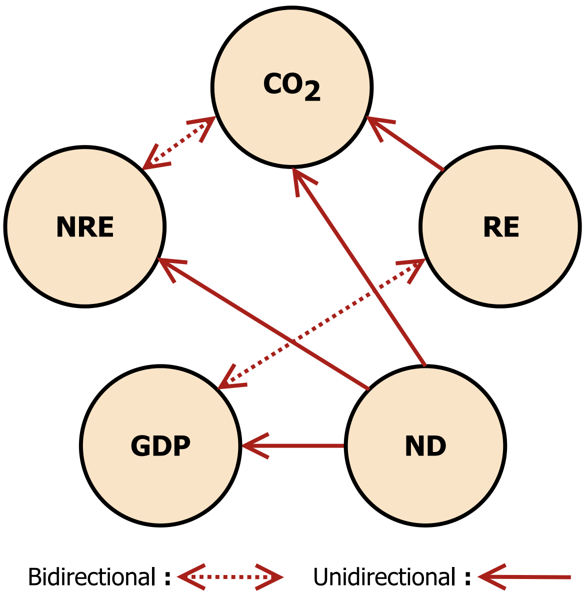

Figure 5. Overview of pairwise Granger causality test.

relationship. The positive impact of CO_2 emissions $Lag_{(-1)}$ implies a delayed positive effect of past CO_2 emissions on current levels, while the negative effect of CO_2 emissions $Lag_{(-2)}$ suggests a more distant historical influence with detrimental consequences. Furthermore, the divergent impacts of renewable and non-renewable energy consumption are striking. Non-renewable energy consumption is associated with increased CO_2 emissions, while renewable energy consumption shows a negative impact, aligning with the global push toward sustainable energy sources.

Economic factors also play a role, with GDP and its lags contributing positively overall. Yet, the negative influence of GDP $Lag_{(-1)}$ adds complexity, hinting at more recent economic activity possibly linked to lower CO_2 emissions. Moreover, the positive correlation between natural disasters $Lag_{(-1)}$ and CO_2 emissions introduces an environmental dimension, indicating a potential connection between regions with a history of natural disasters and higher CO_2 emissions, possibly due to increased industrial activity during short-term recovery periods.

In the long-term context, the findings also highlight the same direction of impact on CO_2 emissions. Non-renewable energy consumption exhibits a positive correlation, suggesting that a 1.0% increase may result in up to a 0.5824% long-term rise in CO_2 emissions, underscoring the urgency for a transition towards more sustainable energy alternatives. The result of this study is supported by [17–22, 72]. Conversely, a 1.0% increase in renewable energy consumption has a negative effect, potentially decreasing CO_2 emissions by up to 0.0740%, prompting further exploration into the complex interplay of factors influencing the environmental impact of clean energy sources. These results align with [29–35]. Policymakers must consider these nuances to develop effective strategies for integrating renewable energy into existing systems while mitigating potential challenges [73, 74].

This study also gauges the challenge of decoupling economic growth from environmental consequences.

With a 1.0% increase in GDP potentially leading to as much as 0.5973% long-term rise in CO_2 emissions, there is a pressing need to explore sustainable practices and technologies. This aligns with [39–47]. Additionally, contrary to expectations, natural disasters might have a positive effect on CO_2 emissions in the long term, despite the specific numbers of empirical results found, with a 1.0% increase leading to up to a 0.0150% increase, suggesting that the impact is relatively small. Efforts to mitigate natural disasters should include scientific analysis of their patterns and robust emergency management to reduce their impact on societal development and CO_2 emissions. During reconstruction, it's crucial to avoid inefficient practices that increase CO_2 emissions, focusing instead on low-carbon rebuilding approaches tailored to local conditions. These results support findings by [13, 75].

In addition to presenting more comprehensive empirical results, this study also establishes the existence of bidirectional causality between non-renewable energy consumption and CO_2 emissions. The use of non-renewable energy consumption contributes to increased CO_2 emissions, while rising CO_2 levels may prompt a shift towards renewable alternatives. This aligns with [67, 72, 76, 77]. Similarly, a bidirectional relationship is observed between GDP and renewable energy consumption. Economic growth drives increased investment in renewable energy, fueled by escalating energy needs and environmental concerns. Conversely, adopting renewable energies stimulates economic growth by creating jobs, enhancing energy security, and promoting long-term sustainability. This dynamic establishes a positive feedback loop, where each element continuously supports the other, effectively aligning economic development with environmental stewardship. These results support findings by [78–81].

Furthermore, the study's discovery of a unidirectional causality from renewable energy consumption to reduced CO_2 emissions provides compelling evidence for the environmental benefits of renewable energy. This finding underscores the direct impact of renewables in mitigating climate change by lowering CO_2 emissions. It offers a strong basis for policy decisions, advocating for increased investment in renewable energy as a key strategy for sustainable development. Additionally, it challenges traditional notions of economic growth tied to higher emissions, suggesting that a shift towards renewable sources can foster economic expansion while simultaneously protecting the environment. This insight is vital for guiding energy policies, influencing public opinion, and shaping global environmental initiatives. These results align with [78, 79].

Lastly, unidirectional causality is found from natural disasters to CO_2 emissions, implying that events such as wildfires or volcanic eruptions can contribute to increased CO_2 emissions. The result of this study is supported by [57–59]. Similarly, unidirectional causality from natural disasters to non-renewable energy consumption suggests that occurrences like landslides and earthquakes can disrupt the production and consumption of non-renewable energy sources. This aligns with [82]. Lastly, unidirectional causality is found from natural disasters to GDP, indicating that the economic impact of events like floods or earthquakes can lead to potential changes in GDP. These results support findings by [83–85].

4. Conclusions and Policy Implications

The study reveals that all chosen factors in this study impact CO_2 emissions in Indonesia from 1980 to 2021. Specifically, economic growth and non-renewable energy consumption positively affect CO_2 emissions, both in the short and long term. In contrast, renewable energy consumption aligns with the global movement towards sustainable energy sources and negatively impacts CO_2 emissions, both in the short and long term. Moreover, natural disasters notably impact CO_2 emissions in the short term.

Two bidirectional causalities have been identified: one between economic growth and renewable energy consumption and another between non-renewable energy consumption and CO_2 emissions. These findings emphasize the intricate relationship connecting economic growth, CO_2 emissions, and energy consumption. Furthermore, four unidirectional causal relationships were identified: from renewable energy consumption to CO_2 emissions, and with natural disasters emerging as the central factor influencing economic growth, non-renewable energy consumption, and CO_2 emissions. These results underscore the importance of renewable energy as a key strategy for sustainable development and environmental protection. Additionally, the potential for natural disasters to adversely affect a country's economic growth and exacerbate CO_2 emissions through increased non-renewable energy consumption is evident.

The study highlights Indonesia's urgent need for policy reforms to balance economic development with environmental sustainability, emphasizing the significant impact of the country's energy consumption, particularly non-renewable energy consumption, on its CO_2 emissions. It reveals a positive correlation between economic growth and increased CO_2 emissions due to non-renewable energy consumption, alongside the encouraging role of renewable energy consumption in reducing emissions. Additionally, the study underscores the importance of robust disaster management strategies that lessen reliance on non-renewable energy post-natural disasters, preventing a rise in emissions. Advocating for an integrated approach, it calls for sustainable energy policies, economic planning, and disaster preparedness to ensure Indonesia's economic stability and environmental protection.

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