The impact of the blue economy and renewable energy on CO_2 emissions in Indonesia: An ARDL approach

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Abstract

Indonesia, the largest archipelagic country in the world with rich marine biodiversity, has significant potential for developing a blue economy encompassing aquaculture, sustainable fisheries, and maritime tourism. However, if not managed sustainably, these activities could increase CO_2 emissions. Indonesia is also among the world's highest emitters of greenhouse gases, largely due to deforestation, forest burning for agriculture, and reliance on fossil fuels in the energy sector. Given global commitments to reducing emissions and mitigating climate change, this research explores how the blue economy and the transition to renewable energy can contribute to lowering CO_2 emissions. This study examines both short- and long-term impacts using the Autoregressive Distributed Lag (ARDL) approach. The findings reveal that while increased aquaculture production initially reduces CO_2 emissions due to efficiency gains and environmentally friendly technologies, its long-term effects are more complex and may lead to higher emissions. On the other hand, renewable energy consumption significantly reduces CO_2 emissions in the short and long term. Conversely, higher energy intensity contributes to increased CO_2 emissions, which can be mitigated through improved energy efficiency.

Keywords: *Blue economy, CO_2 emission, Economic growth, Renewable energy*

JEL Classification: O13, Q22, O44, Q54

INTRODUCTION

The Blue Economy, which prioritizes the sustainable use of marine resources, holds significant potential for reducing CO_2 emissions in Indonesia. With an area of 6.4 million km^2, Indonesia has immense potential in fisheries and marine economy (Sari & Muslimah, 2020). Data from the Ministry of Maritime Affairs and Fisheries shows that Indonesia's marine economic potential is valued at Rp3000 trillion, with Rp291.8 trillion already realized. The Blue Economy advocates for environmentally friendly practices in the maritime sector, including fisheries, tourism, and renewable energy such as wave power and offshore wind (Spalding, 2016). Alongside increased use of renewable energy on land, the Blue Economy can significantly reduce greenhouse gas emissions (Hossain et al., 2024). Sustainable fisheries development must adhere to principles that ensure benefits for the current generation while maintaining sustainability for future generations (Cooke et al., 2023). Blue Economy policies and programs represent an appropriate and effective approach to marine development, promoting the optimal and sustainable use of fishery resources (Wenhai et al., 2019). Thus, incorporating Blue Economy principles into national strategies can help Indonesia reduce CO2 emissions while maximizing the economic benefits of its marine resources.

CO2 emissions in Indonesia are concerning, as the country is the 9th largest contributor to CO2 emissions globally. The energy sector is responsible for most greenhouse gas emissions due to fossil fuel combustion (Malik et al., 2016). In Indonesia, most CO2 emissions from the energy sector come from burning coal, oil, and natural gas for power generation and as fuel for vehicles and machinery (Deendarlianto et al., 2017). In 2021, coal became Indonesia's largest source of CO2 emissions, accounting for 51% of total CO2 emissions from fuel combustion (Figure 1).

High CO2 emissions in Indonesia have led to serious environmental and health problems (Haryanto, 2018). Fossil fuel combustion, the primary source of these emissions, produces air pollution that negatively impacts public health (Lelieveld et al., 2019). Moreover, elevated greenhouse gas emissions accelerate climate change, significantly affect weather patterns, and increase the frequency and severity of natural disasters such as floods and droughts (Hussain et al., 2020). This climate change also threatens biodiversity by destroying natural habitats (Rawat & Agarwal, 2015). Given these impacts, Indonesia must adopt renewable energy sources and reduce energy intensity swiftly. Renewable energy, such as solar, wind, and biomass, can decrease reliance on fossil fuels and lower CO2 emissions while supporting environmental sustainability and public health (Holechek et al., 2022). This strategy is key for achieving sustainable development and effective climate change mitigation in Indonesia.

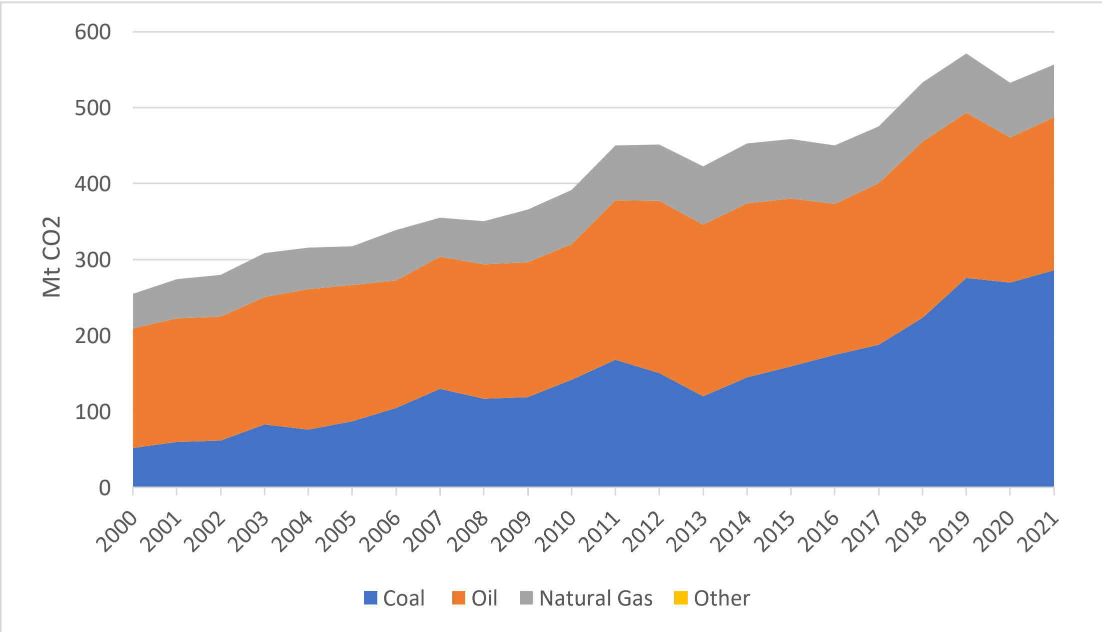

Figure 1. The evolution of CO2 emissions from fuels in Indonesia since 2000
Source: International Energy Agency, (2024)

Increasing the consumption of renewable energy sources, such as solar, wind, and biomass, offers a sustainable solution crucial in reducing dependence on fossil fuels and significantly lowering CO2 emissions. The potential of solar energy in developing countries for reducing energy-related emissions is particularly notable (Shahsavari &

Akbari, 2018). Renewable energy provides a cleaner and more sustainable alternative to conventional energy sources that pollute the environment (Dincer & Pickles, 2015). The development and implementation of this technology can substantially reduce Indonesia's carbon footprint, as the country is one of the world's largest CO2 emitters (Raihan et al., 2022). Additionally, improving energy efficiency by adopting advanced technologies and better energy management practices can reduce total energy consumption without hindering economic growth (Lee & Cheng, 2016). This approach includes using energy-saving devices, improving energy management systems in the industrial sector, and implementing policies that support energy efficiency across various sectors (Javied et al., 2015).

Indonesia can balance economic development and environmental protection by integrating renewable energy into national energy consumption and optimizing energy efficiency. This will promote the domestic environment's sustainability and contribute to global efforts to address climate change. This approach highlights the importance of a comprehensive energy transition, including diversifying energy sources, technological innovation, and implementing policies and regulations supporting green energy transformation. This way, Indonesia can serve as a model for a developing country that successfully combines economic growth with high environmental responsibility.

Indonesia's economic growth over the past few decades has driven an increase in energy consumption, contributing to rising CO2 emissions (Vo et al., 2019). As the economy grows, so does energy demand from industries, transportation, and households (Sorrell, 2015). However, much of this energy demand is still met through the combustion of fossil fuels like coal, oil, and natural gas, the main sources of CO2 emissions. According to the Environmental Kuznets Curve (EKC) theory, CO2 emissions initially increase as the economy grows but begin to decline once a certain income level is reached, allowing for greater investment in clean technologies and the implementation of stricter environmental regulations (Ahmad et al., 2021; Shahbaz & Sinha, 2019). Thus, investment in renewable energy and energy efficiency technologies is crucial, as it can help reduce the carbon intensity of economic growth, allowing progress without sacrificing the environment.

The Blue Economy offers an approach to achieving sustainable economic growth through the environmentally friendly use of marine resources (Elegbede et al., 2023). By encouraging sustainable fisheries, responsible aquaculture, and renewable marine energy, the Blue Economy seeks to reduce environmental impact while supporting economic growth. The concept also focuses on reducing CO2 emissions by optimizing cleaner and more efficient marine resources, such as offshore wind and wave energy. Implementing the Blue Economy can help Indonesia significantly reduce CO2 emissions while maintaining economic development targets, making it a key component of the national strategy for sustainable and environmentally friendly development.

Although there is extensive research on CO2 emissions and mitigation strategies in Indonesia, most of it emphasizes the conventional energy sector and short-term solutions, such as fuel switching or energy efficiency (Maulidia et al., 2019; Rahman et al., 2023). Previous research has explored the relevance of energy and Blue Economy indicators to carbon neutrality in specific contexts, such as Saudi Arabia, suggesting that these sectors are not yet mature enough to achieve carbon emission reduction goals before implementing Vision 2030 (Sarwar et al., 2022). Other studies have used the asymmetrical panel ARDL technique to investigate the role of energy and green and blue economic factors in GCC countries in achieving sustainable growth, emphasizing the importance of grants, marine trade, and marine tourism in sustainable economic development after Vision 2030 (Sarwar, 2022). However, a significant research gap remains concerning the long-term impact of the Blue Economy and renewable energy on CO2 emissions in Indonesia. Prior studies have often overlooked the potential contribution of Blue Economy sectors, such as sustainable fisheries, marine tourism, and marine ecosystem conservation, in reducing carbon emissions. Moreover, they have tended to neglect how the energy transition from fossil fuels to renewable energy sources like solar, wind, and bioenergy can sustainably reduce CO2 emissions in the long term. Therefore, this study aims to fill this gap by comprehensively evaluating the role of the Blue Economy and renewable energy in reducing CO2 emissions, using the ARDL approach, which allows for simultaneous analysis of short-term and long-term relationships.

This study seeks to answer the primary question: How do the Blue Economy and energy transition affect CO2 emissions in Indonesia? Specifically, the study hypothesizes that implementing the Blue Economy and increasing the use of renewable energy will significantly reduce CO2 emissions in Indonesia. Furthermore, the study also considers the role of GDP as a control variable that could moderate the relationship between the Blue Economy, energy transition, and CO2 emissions. This study uses the ARDL approach to explore these strategies' short-term and long-term effects on CO2 emissions. The findings are expected to provide deeper insights into the effectiveness of the Blue Economy and energy transition in mitigating climate change in Indonesia, offering a solid foundation for formulating more sustainable environmental policies.

METHODS

This study aims to analyze the influence of the blue economy and energy transition on CO2 emissions in Indonesia, using the variables described in Table 1. The study uses secondary data spanning from 1990 to 2022. This time frame was selected to capture key policy changes and significant technological advancements in Indonesia's Blue Economy and energy transition sectors. However, there are potential limitations, such as the availability and accuracy of data, particularly for certain variables like aquaculture production. Historical data may be inconsistent due to varying data collection methods across years, potentially affecting the robustness of the findings. Addressing these data limitations is essential for a more comprehensive understanding of the study's implications.

The Autoregressive Distributed Lag (ARDL) model analysis technique is applied in this study. According to the concept presented by Gujarati and Porter, the ARDL model is used to analyze the influence of exogenous variables on endogenous variables over time, including the influence of past values of the dependent variable (Y) on current values of Y. Data was processed using EViews software, version 12.

The ARDL model was chosen based on the data characteristics, allowing for short-term and long-term relationships between independent and dependent variables. This model is flexible in handling variables with different integration orders (I(0) or I(1)) without requiring pre-cointegration testing. Model selection criteria involve stationarity testing and optimal lag selection based on information criteria such as AIC and SIC. The key coefficients in the ARDL model offer both short-term and long-term insights: short-term coefficients reflect the response of dependent variables to exogenous changes over time, while long-term coefficients reveal equilibrium relationships between variables over extended periods.

In analyzing the ARDL model, it is crucial to address potential endogeneity issues that could affect the accuracy of coefficient estimations. Endogeneity can arise if an independent variable correlates with the error term due to omitted variables, measurement errors, or a bidirectional causal relationship between variables. For instance, in this study, Blue Economy and energy transition variables may not be entirely exogenous to CO2 emissions due to complex reciprocal relationships or other factors that influence both. The study includes control variables, such as GDP, to mitigate this issue, as GDP is known to affect CO2 emissions significantly. Using GDP as a control variable helps reduce the risk of endogenous bias by capturing the effect of economic growth on emissions, leading to more accurate estimates and avoiding model specification errors.

Table 1. Variable operational

	Variable	Variable description	Data sources
Explained Variable	CO2	CO2 emissions (metric tons per capita)	World Bank
Explanatory Variable	AP	Aquaculture Production (AP)	World Bank
	REN	Renewable energy consumption (% of total final energy consumption)	World Bank
	IE	The energy intensity level of primary energy (MJ/$2017 PPP GDP)	World Bank
Control Variable	EG	GDP per capita (constant LCU)	World Bank

Aquaculture Production (AP) was selected due to its role in the blue economy, which has lower environmental impacts than traditional fishing methods. Renewable Energy Consumption (REN) is directly linked to CO2 emission reductions through cleaner energy sources. Energy Intensity (IE) measures the efficiency of energy use in the economy, providing insights into the effects of energy efficiency on carbon emissions, more specifically than simply assessing total energy consumption. GDP per capita (EG) is used as a control variable to account for the impact of economic development on CO2 emissions independently of energy and aquaculture factors, thereby improving the accuracy of the analysis.

In this study, the ARDL model is used to assess the effects of various factors on CO2 emissions. The main equation of the model is as follows:

$$CO2_t = \alpha_0 + \alpha_1 lnAP_t + \alpha_2 lnREN_t + \alpha_2 lnIE_t + \alpha_{i-j} X_{i-jt} + e_t \text{ ....(1)}$$

Where:
$CO2_t$ is CO2 emissions; AP is aquaculture production; REN is renewable energy consumption; IE is energy intensity; X_{i-jt} is the control variable, using economic growth proxied using GDP per capita, t represents the time series, e is the error term. The coefficients (α) measure the long-term impact of aquaculture production, renewable energy consumption, energy intensity, and economic growth on CO2 emissions, indicating how these variables affect emissions over time.

The ARDL model also captures both short-term and long-term effects through the following equation:

$$\Delta CO2_t = \gamma_0 + \alpha_0 CO2_{t-1} + \alpha_1 lnAP_t + \alpha_2 lnREN_t + \alpha_3 IE_t + \alpha_4 lnEG_t + \sum_{i=1}^{n} \rho_0 \Delta CO2_{t-1} + \sum_{i=1}^{n} \rho_1 \Delta lnAP_{t-1} + \sum_{i=1}^{n} \rho_2 \Delta lnREN_{t-1} + \sum_{i=1}^{n} \rho_3 \Delta lnIE_{t-1} + \Delta lnEG_{t-1} \text{ .... (2)}$$

In this model, $\Delta CO2_t$ represents the change in CO2 emissions from one period to the next. The coefficients $\alpha_{1,2,3,4}$ capture the short-term effects of aquaculture production, renewable energy consumption, energy intensity, and economic growth on CO2 emissions. The summation terms, $\sum_{i=1}^{n} \rho_0 \, \Delta CO2_{t-1}$ and similar terms account for the cumulative impact of past changes in these variables on current CO2 emissions. Intuitively, the α coefficients indicate how immediate changes in these variables affect CO2 emissions. In contrast, the ρ coefficients measure how variations from previous periods influence the current level of emissions, offering insight into the persistence of these effects over time.

Finally, the ARDL model incorporates the Error Correction Term (ECT) to assess the speed at which the system returns to equilibrium after deviations:

$$\Delta CO2_t = \vartheta_0 + \sum_{i=1}^{n} \gamma_{0i} \, \Delta CO2_{t-1} + \sum_{i=1}^{n} \gamma_{1i} \, \Delta lnAP_{t-1} + \sum_{i=1}^{n} \gamma_{2i} \, \Delta lnREN_{t-1} + \sum_{i=1}^{n} \gamma_{3i} \Delta IE_{t-1} + \sum_{i=1}^{n} \gamma_{4i} \Delta lnEG_{t-1} + \delta ect_{t-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

In this equation, δ represents the Error Correction Term (ECT) coefficient, which indicates the speed at which the system returns to equilibrium following deviations. A theoretically significant and negative δ value suggests that imbalances are corrected effectively, ensuring that short-term deviations are addressed and the system moves toward long-term equilibrium.

RESULTS AND DISCUSSION

Estimated results

The results of the unit root test, using both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) methods, showed that the dependent variable (CO2 emissions) and independent variables (lnAP, lnREN, IE, and lnEG) are all stationary at the first difference, or I(1) (Table 2). These variables require a first-difference transformation to remove trends and unit roots. Stationarity at the first difference (I(1)) indicates that the data exhibits a pattern that necessitates transformation to achieve stationarity. In the context of the ARDL model, this is not problematic since the ARDL method can handle variables with different integration orders simultaneously. Therefore, the ARDL model can estimate short-term and long-term relationships without requiring prior cointegration tests.

However, when interpreting the results, it is important to consider that stationary variables at the first difference reflect long-term trends. These trends influence the long-term coefficients in the model. In other words, although first-differenced stationary variables affect the estimation process, the ARDL model remains appropriate for analyzing the impact of the Blue Economy and energy transition on CO2 emissions.

Table 2. Unit root test results

Variable	Augmented Dickey-Fuller		Phillips-Perron	
	level	1st difference	level	1st difference
CO2	-1.3043	-4.8272***	-1.0269	-15.1333***
lnAP	-9.9119	-2.7934**	-0.5140	-2.7753**
lnREN	1.0029	-6.7238***	4.0636	-6.8596***
IE	0.7922	-2.4637**	-0.6653	-3.5234**
lnEG	-0.1430	-4.2107***	-0.1563	-4.1476***

*Note: ***, ** indicate significance at the 1% and 5% levels, respectively.*

The selection of the optimal lag length in this study was determined using the Akaike Information Criteria (AIC), as shown in Table 3. Based on Figure 2, the maximum lag length selected for the various variables is 3, 3, 0, 1, and 2. The use of AIC as a lag selection criterion is justified by its ability to identify parsimonious and efficient models, reducing model complexity while minimizing estimation errors. The model with the selected lag length provides the best balance between model fit and complexity.

The results of the ARDL bound test indicate that the estimated F-statistic exceeds the critical bounds for both I(0) and I(1), reaching 15.3826 at a 1% significance level. This suggests that the null hypothesis of no cointegration is rejected, confirming the presence of a cointegrating relationship in the model. The robustness of the results can be confirmed by testing alternative models with different lag lengths; if cointegration conclusions remain consistent, it strengthens the validity of the model. However, the model with the optimal lag length, based on AIC, is better suited to explain the long-term relationships between the variables in this study effectively and efficiently.

Table 3. ARDL Bound test cointegration results

ARDL Bound Test Model	**Lag selection**	**F-Stat**
$CO2_t = f(lnAP_t, lnREN_t, lnIE_t, lnEG_t)$	3, 3, 0, 1, 2	15.3826***
Critical Value Bounds		
Significance	**I(0)**	**I(1)**
10%	2.2	3.09
5%	2.56	3.49
2.5%	2.88	3.87
1%	3.29	4.37

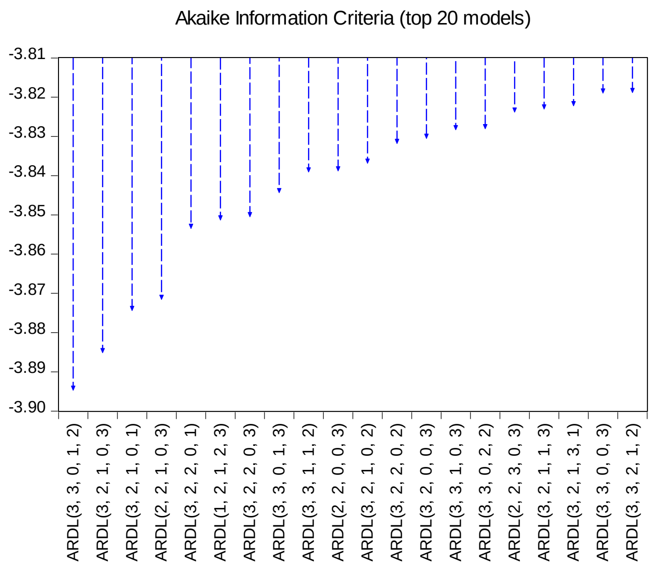

Figure 2. Akaike Information Criteria (Top 20 Model)

The results of the short- and long-term model estimates and the diagnostic tests are presented in Table 4. The short-term estimation indicates that the error correction term (ECT) has a negative coefficient of -9.8165, statistically significant at the 1% confidence level. This suggests that any imbalance in the model will be corrected, reaching equilibrium in approximately 9.81 years. Furthermore, the CO2 variable significantly affects lag 3 in the short term. The lnAP variable has a positive and significant coefficient at lag 3, indicating a delayed but significant influence. Meanwhile, lnREN exhibits a negative and significant impact at lag 0, suggesting an immediate effect, while IE has a positive and significant influence at lag 1. The control variable, lnEG, negatively affects CO2 at lag 2 in the short term.

Table 4. Long and short-run ARDL estimation

Dependent variable = CO2			
Long-run			
Variable	**Coef.**	**Std. Error**	**t-Stat.**
C	-5.6139***	1.2693	-4.4226
lnAP	-0.0375*	0.0196	-1.9135
lnREN	-0.5389***	0.1418	8.0250
IE	0.9091***	0.0717	12.6736
lnEG	1.1386	0.0196	1.9135
Short-run			
Δ(CO2)	0.2186**	0.0878	2.4882
Δ(lnAP)	0.1942**	0.0081	2.2028
Δ(lnREN)	-0.9423***	0.1553	-6.0659
Δ(lnIE)	0.8837***	0.2837	3.1143
Δ(lnEG)	-0.7609**	0.2828	-2.6904
ECTt-1	-9.8165***	2.6761	-3.6681
Diagnostic test			
Test	**F-stat.**		**Prob.**
LM test			
Normality test	1.9758		0.5189
Heteroscedasticity test	1.3983		0.0823
Ramsey RESET test	8.2891		0.1150

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

In the long term, lnAP and lnREN have negative and significant coefficients, indicating their negative impact on CO2 emissions. Conversely, IE has a positive and significant influence, suggesting increased energy intensity is associated with higher CO2 emissions. The positive coefficient for IE implies that although energy efficiency may improve, it can inadvertently lead to increased CO2 emissions unless complemented by greater renewable energy use. Therefore, policies focusing on energy efficiency must also prioritize expanding renewable energy technologies to mitigate potential negative effects on carbon emissions. The control variable lnEG, shows a positive but statistically insignificant impact on CO2 emissions in the long term, suggesting that economic growth alone may not substantially influence CO2 emissions unless accompanied by structural changes in energy consumption and production.

Table 4 also includes results from several diagnostic tests, confirming the validity of the research model. The normality test (p-value = 0.5189) indicates that the residuals are normally distributed. The heteroscedasticity test (p-value = 0.0823) suggests that the residuals exhibit constant variance, meaning no heteroscedasticity issue exists. The Ramsey RESET test (p-value = 0.1150) shows no significant specification errors in the model. These diagnostic results confirm that the model is robust and reliable for further analysis.

The stability of the ARDL model was assessed using the CUSUM and CUSUM of Squares tests (Figure 3). The results show that the CUSUM and CUSUM of Squares lines remain within the 5% significance boundaries throughout the period, indicating that the model is stable and does not experience significant structural changes over time. This confirms the long-term stability of the model's estimated parameters, ensuring the reliability of the results.

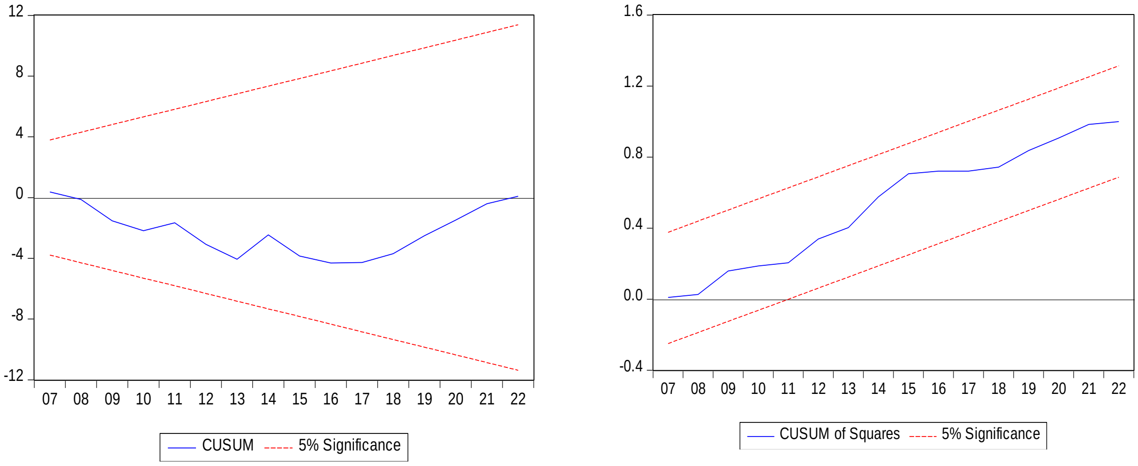

Figure 3. Cumulative sum of recursive residuals (CUSUM)

Discussion

The discussion of the results highlights the varying effects of aquaculture production, renewable energy consumption, energy intensity, and economic growth on CO2 emissions in Indonesia, both in the short and long term.

In the short term, aquaculture production positively and significantly impacts CO2 emissions. This is largely due to the intensification of production, which demands more energy and resources. Energy is required to maintain aquaculture infrastructure, environmental conditions, and waste management systems. Operations and transportation often rely on fossil fuels, further contributing to emissions (Little et al., 2017). Additionally, unsustainable practices, such as using chemical fertilizers, antibiotics, and illegal fishing for feed, increase emissions (Boyd et al., 2020). Overfishing disrupts ecosystems and affects the carbon cycle in aquatic environments, leading to a higher carbon footprint. These findings align with previous studies (Badîrcea et al., 2021; Bhattacharya & Dash, 2020).

However, in the long term, the relationship between aquaculture production and CO2 emissions becomes more complex. The environmental impact can be reduced as the industry moves towards sustainable and efficient practices. For example, adopting environmentally friendly management practices, such as more efficient feed use, reduced chemical reliance, and stricter regulations on illegal fishing, can help lower the industry's carbon footprint. Investments in energy-efficient technologies and a transition to renewable energy further mitigate CO2 emissions. The European Union's investments in aquaculture technology, including more efficient marine cage systems and recirculating aquaculture systems, serve as a valuable example of how these changes can lead to reduced environmental impacts (Bostock et al., 2016). Thus, while aquaculture may increase emissions in the short term, long-term sustainable strategies can significantly decrease its carbon footprint.

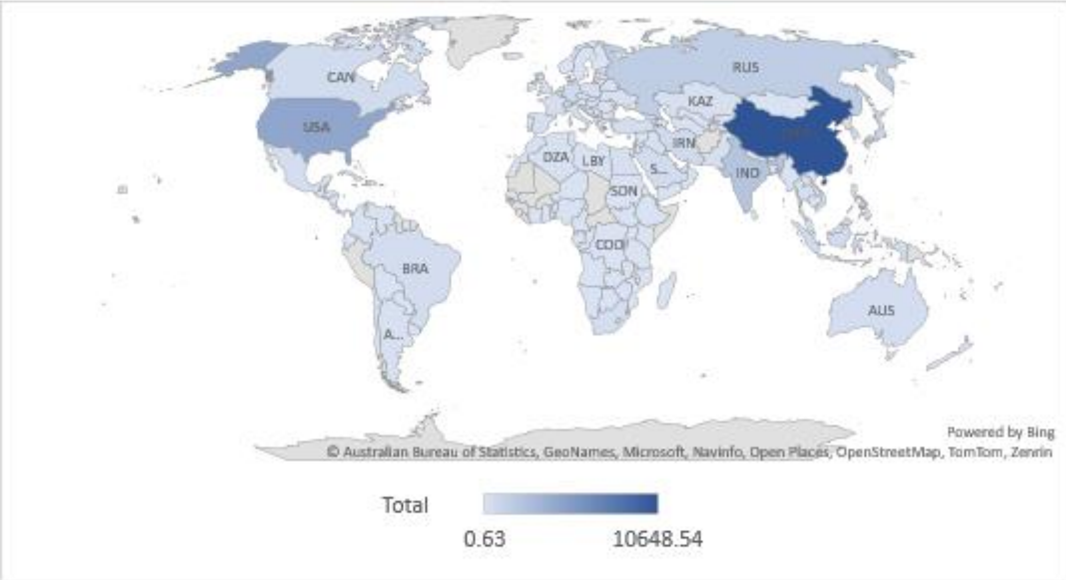

Figure 4. CO2 emissions from fuel combustion, regional ranking, 2021
Source: International Energy Agency, data processed (2024)

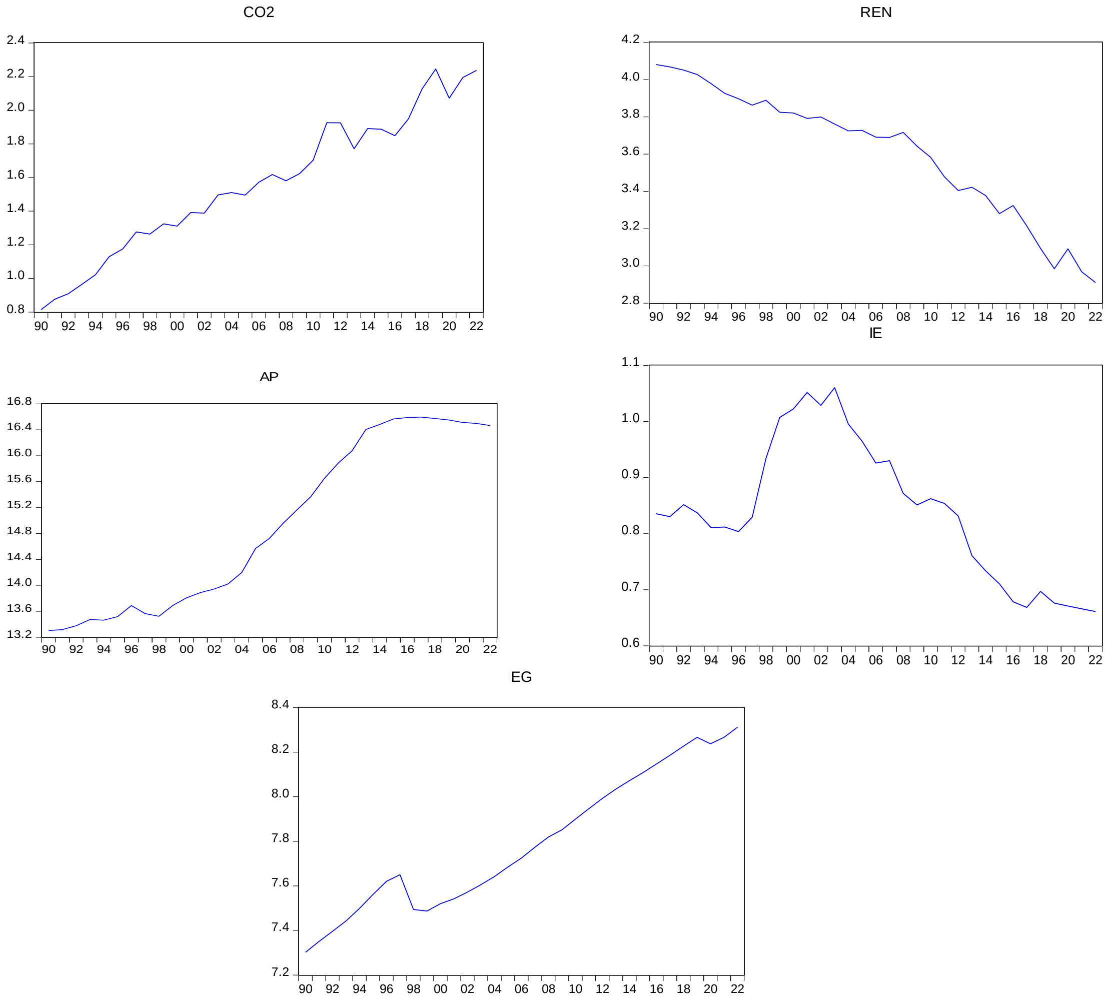

Figure 5. Movement of CO2 emission variables, aquaculture production, renewable energy consumption, energy intensity, economic growth

Renewable energy consumption negatively and significantly influences CO2 emissions in the short and long term. This underscores the importance of increasing renewable energy usage to lower emissions. In the short term, technologies such as solar, wind, and biomass reduce dependence on fossil fuels, directly reducing greenhouse gas emissions (Idroes et al., 2024; Saudi et al., 2019). In the long term, renewable energy promotes greater efficiency through improvements in energy infrastructure and the development of sustainable green technologies. Government policies, such as fiscal incentives and green energy projects, are critical in accelerating renewable energy adoption (Abdmouleh et al., 2015; Abolhosseini & Heshmati, 2014).

Despite Indonesia's significant greenhouse gas emissions, mainly from deforestation and fossil fuel reliance, the growing use of renewable energy presents an opportunity to significantly lower emissions. Renewable energy could reduce Indonesia's reliance on coal and petroleum, the primary energy sector emissions sources (Rahman et al., 2023b). However, challenges such as low investment in the energy sector, technological hurdles, and institutional barriers slow the transition to renewable energy. The government has set ambitious goals to increase renewable energy usage to 23% by 2025 and 31% by 2050, but achieving these targets will require clear policies, mandates, and significant investment (Raihan et al., 2023).

Energy intensity positively and significantly influences CO2 emissions in the short and long term. Reducing energy intensity, which measures the energy needed to produce one unit of economic output, is associated with decreased CO2 emissions. In the short term, this can be achieved by improving energy efficiency in industrial processes, transportation, and household use, directly reducing fossil fuel consumption and emissions (Fais et al., 2016). Long-term reductions in energy intensity can be achieved through improvements in energy infrastructure, the adoption of low-carbon technologies, and policies that promote energy conservation (Shahbaz et al., 2020; Danish et al., 2020).

Indonesia's energy intensity is lower than that of neighboring countries such as Vietnam and Thailand but still higher than Singapore and the Philippines (Santika et al., 2020). The National Energy Policy targets a 1% annual reduction in energy intensity, with initiatives promoting energy efficiency in the private and public sectors (Nurcahyanto et al., 2020). As energy efficiency improves, CO2 emissions can decrease without negatively impacting economic growth, making energy intensity a key area for Indonesia's climate change mitigation strategies.

Economic growth positively and significantly affects CO2 emissions in the short and long term. As economic activity increases, so do energy consumption and emissions. In the short term, industrial production, trade, and transportation are typically accompanied by increased fossil fuel use, leading to higher CO2 emissions (Mikayilov et al., 2018; Aye & Edoja, 2017). Long-term economic growth sustains this trend, with growing energy demands across sectors. Despite Indonesia's efforts to adopt renewable energy and improve energy efficiency, economic growth continues to drive up CO2 emissions.

This pattern is similar in Southeast Asian countries, such as Vietnam and Thailand, where industrialization and economic growth have increased emissions (Quy et al., 2024). However, Thailand's adoption of low-carbon technologies and fiscal policies promoting renewable energy has helped reduce its environmental impact (Chien et al., 2023). Vietnam’s shift towards sustainable aquaculture has also reduced long-term CO2 emissions despite initial increases from production intensification (Henriksson et al., 2018). Indonesia can learn from these experiences by further integrating green policies, investing in renewable technologies, and promoting energy efficiency to achieve sustainable economic growth without exacerbating CO2 emissions.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study reveals that aquaculture production in Indonesia has varying impacts on CO2 emissions in the short and long term. In the short term, increasing aquaculture production tends to reduce CO2 emissions due to initial efficiency gains and using environmentally friendly technology. However, in the long term, intensified production and unsustainable management practices contribute to more complex effects, potentially increasing emissions. Furthermore, renewable energy consumption in Indonesia has a negative and significant influence on CO2 emissions, both in the short and long term, highlighting the substantial role renewable energy plays in reducing emissions. Conversely, energy intensity positively influences CO2 emissions, indicating that energy efficiency, infrastructure, and technology improvements are necessary to reduce emissions. Lastly, economic growth positively affects CO2 emissions, as increased economic activity drives higher energy consumption and fossil fuel use.

This study shows that aquaculture production in Indonesia has different impacts on CO2 emissions in the short and long term; where in the short term, increasing aquaculture production reduces CO2 emissions thanks to initial efficiency and environmentally friendly technology, while in the long term, the impact becomes more complex due to intensified production and unsustainable management practices. In addition, renewable energy consumption in Indonesia shows a negative and significant influence on CO2 emissions in both the short and long term, indicating that increasing the use of renewable energy can significantly reduce CO2 emissions. In contrast, energy intensity positively influences CO2 emissions, meaning that a decrease in energy intensity correlates with a decrease in CO2 emissions. This can be achieved through an increase in energy efficiency through infrastructure improvement, adoption of efficient technology, and energy-saving policies. Economic growth in Indonesia also has a positive and significant effect on CO2 emissions, where increased economic activity increases CO2 emissions due to increased energy consumption and the use of fossil fuels.

Recommendations

A comprehensive and sustainable strategy is necessary to reduce CO2 emissions while ensuring sustainable economic growth in Indonesia. In the aquaculture sector, it is crucial to implement more environmentally friendly management practices, such as using sustainable feeds, reducing chemical usage, and enforcing stricter monitoring of illegal fishing. Investments in green technologies are also recommended to improve production efficiency without raising CO2 emissions.

Investing in solar, wind, and biomass energy should expand renewable energy consumption. This can be achieved through government policies that provide fiscal incentives and support green energy projects. Moreover, energy efficiency should be prioritized across industrial, transportation, and household sectors by adopting efficient technologies and developing better energy infrastructure.

However, implementing these policies may encounter political resistance and financial constraints. Mitigation strategies should focus on overcoming these challenges by increasing public awareness and support for environmental policies, strengthening institutional capacity for effective policy implementation, and creating innovative funding schemes to facilitate investments in green technologies and renewable energy. The government should also develop a regulatory framework that incentivizes companies and communities to adopt greener practices. By integrating these measures, Indonesia can more effectively balance economic growth and environmental sustainability.

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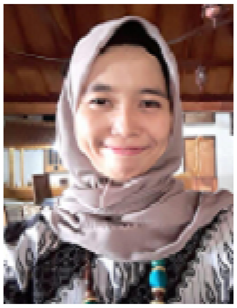

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The impact of the blue economy and renewable energy on CO2 emissions in Indonesia: An ARDL approach

by Anna Yulianita

The impact of the blue economy and renewable energy on CO2 emissions in Indonesia: An ARDL approach

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Abstract

Indonesia, the largest archipelagic country in the world with rich marine biodiversity, has significant potential for developing a blue economy encompassing aquaculture, sustainable fisheries, and maritime tourism. However, if not managed sustainably, these activities could increase CO2 emissions. Indonesia is also among the world's highest emitters of greenhouse gases, largely due to deforestation, forest burning for agriculture, and reliance on fossil fuels in the energy sector. Given global commitments to reducing emissions and mitigating climate change, this research explores how the blue economy and the transition to renewable energy can contribute to lowering CO2 emissions. This study examines both short- and long-term impacts using the Autoregressive Distributed Lag (ARDL) approach. The findings reveal that while increased aquaculture production initially reduces CO2 emissions due to efficiency gains and environmentally friendly technologies, its long-term effects are more complex and may lead to higher emissions. On the other hand, renewable energy consumption significantly reduces CO2 emissions in the short and long term. Conversely, higher energy intensity contributes to increased CO2 emissions, which can be mitigated through improved energy efficiency.

Keywords: *Blue economy, CO2 emission, Economic growth, Renewable energy*

JEL Classification: O13, Q22, O44, Q54

INTRODUCTION

The Blue Economy, which prioritizes the sustainable use of marine resources, holds significant potential for reducing CO2 emissions in Indonesia. With an area of 6.4 million km², Indonesia has immense potential in fisheries and marine economy (Sari & Muslimah, 2020). Data from the Ministry of Maritime Affairs and Fisheries shows that Indonesia's marine economic potential is valued at Rp3000 trillion, with Rp291.8 trillion already realized. The Blue Economy advocates for environmentally friendly practices in the maritime sector, including fisheries, tourism, and renewable energy such as wave power and offshore wind (Spalding, 2016). Alongside increased use of renewable energy on land, the Blue Economy can significantly reduce greenhouse gas emissions (Hossain et al., 2024). Sustainable fisheries development must adhere to principles that ensure benefits for the current generation while maintaining sustainability for future generations (Cooke et al., 2023). Blue Economy policies and programs represent an appropriate and effective approach to marine development, promoting the optimal and sustainable use of fishery resources (Wenhai et al., 2019). Thus, incorporating Blue Economy principles into national strategies can help Indonesia reduce CO2 emissions while maximizing the economic benefits of its marine resources.

CO2 emissions in Indonesia are concerning, as the country is the 9th largest contributor to CO2 emissions globally. The energy sector is responsible for most greenhouse gas emissions due to fossil fuel combustion (Malik et al., 2016). In Indonesia, most CO2 emissions from the energy sector come from burning coal, oil, and natural gas for power generation and as fuel for vehicles and machinery (Deendarlianto et al., 2017). In 2021, coal became Indonesia's largest source of CO2 emissions, accounting for 51% of total CO2 emissions from fuel combustion (Figure 1).

High CO2 emissions in Indonesia have led to serious environmental and health problems (Haryanto, 2018). Fossil fuel combustion, the primary source of these emissions, produces air pollution that negatively impacts public health (Lelieveld et al., 2019). Moreover, elevated greenhouse gas emissions accelerate climate change, significantly affect weather patterns, and increase the frequency and severity of natural disasters such as floods and droughts (Hussain et al., 2020). This climate change also threatens biodiversity by destroying natural habitats (Rawat & Agarwal, 2015). Given these impacts, Indonesia must adopt renewable energy sources and reduce energy intensity swiftly. Renewable energy, such as solar, wind, and biomass, can decrease reliance on fossil fuels and lower CO2 emissions while supporting environmental sustainability and public health (Holechek et al., 2022). This strategy is key for achieving sustainable development and effective climate change mitigation in Indonesia.

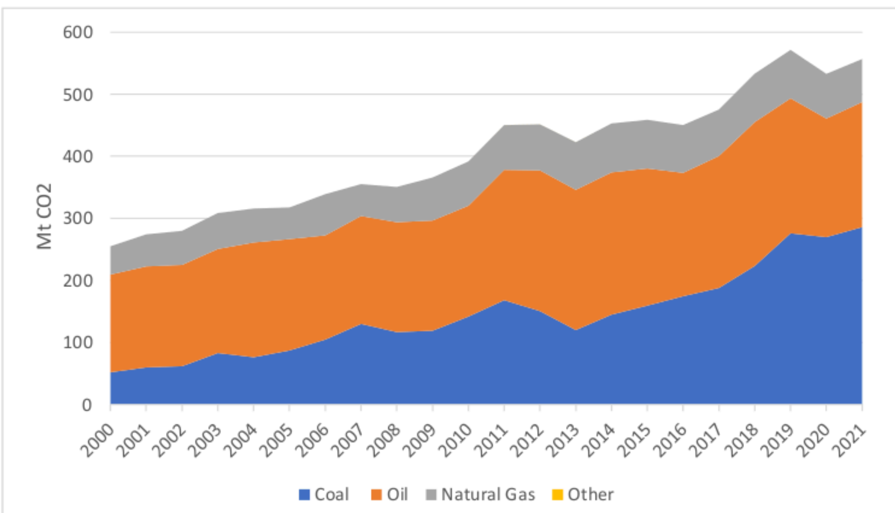

Figure 1. The evolution of CO2 emissions from fuels in Indonesia since 2000
Source: International Energy Agency, (2024)

Increasing the consumption of renewable energy sources, such as solar, wind, and biomass, offers a sustainable solution crucial in reducing dependence on fossil fuels and significantly lowering CO2 emissions. The potential of solar energy in developing countries for reducing energy-related emissions is particularly notable (Shahsavari &

Akbari, 2018). Renewable energy provides a cleaner and more sustainable alternative to conventional energy sources that pollute the environment (Dincer & Pickles, 2015). The development and implementation of this technology can substantially reduce Indonesia's carbon footprint, as the country is one of the world's largest CO2 emitters (Raihan et al., 2022). Additionally, improving energy efficiency by adopting advanced technologies and better energy management practices can reduce total energy consumption without hindering economic growth (Lee & Cheng, 2016). This approach includes using energy-saving devices, improving energy management systems in the industrial sector, and implementing policies that support energy efficiency across various sectors (Javied et al., 2015).

Indonesia can balance economic development and environmental protection by integrating renewable energy into national energy consumption and optimizing energy efficiency. This will promote the domestic environment's sustainability and contribute to global efforts to address climate change. This approach highlights the importance of a comprehensive energy transition, including diversifying energy sources, technological innovation, and implementing policies and regulations supporting green energy transformation. This way, Indonesia can serve as a model for a developing country that successfully combines economic growth with high environmental responsibility.

Indonesia's economic growth over the past few decades has driven an increase in energy consumption, contributing to rising CO2 emissions (Vo et al., 2019). As the economy grows, so does energy demand from industries, transportation, and households (Sorrell, 2015). However, much of this energy demand is still met through the combustion of fossil fuels like coal, oil, and natural gas, the main sources of CO2 emissions. According to the Environmental Kuznets Curve (EKC) theory, CO2 emissions initially increase as the economy grows but begin to decline once a certain income level is reached, allowing for greater investment in clean technologies and the implementation of stricter environmental regulations (Ahmad et al., 2021; Shahbaz & Sinha, 2019). Thus, investment in renewable energy and energy efficiency technologies is crucial, as it can help reduce the carbon intensity of economic growth, allowing progress without sacrificing the environment.

The Blue Economy offers an approach to achieving sustainable economic growth through the environmentally friendly use of marine resources (Elegbede et al., 2023). By encouraging sustainable fisheries, responsible aquaculture, and renewable marine energy, the Blue Economy seeks to reduce environmental impact while supporting economic growth. The concept also focuses on reducing CO2 emissions by optimizing cleaner and more efficient marine resources, such as offshore wind and wave energy. Implementing the Blue Economy can help Indonesia significantly reduce CO2 emissions while maintaining economic development targets, making it a key component of the national strategy for sustainable and environmentally friendly development.

Although there is extensive research on CO2 emissions and mitigation strategies in Indonesia, most of it emphasizes the conventional energy sector and short-term solutions, such as fuel switching or energy efficiency (Maulidia et al., 2019; Rahman et al., 2023). Previous research has explored the relevance of energy and Blue Economy indicators to carbon neutrality in specific contexts, such as Saudi Arabia, suggesting that these sectors are not yet mature enough to achieve carbon emission reduction goals before implementing Vision 2030 (Sarwar et al., 2022). Other studies have used the asymmetrical panel ARDL technique to investigate the role of energy and green and blue economic factors in GCC countries in achieving sustainable growth, emphasizing the importance of grants, marine trade, and marine tourism in sustainable economic development after Vision 2030 (Sarwar, 2022). However, a significant research gap remains concerning the long-term impact of the Blue Economy and renewable energy on CO2 emissions in Indonesia. Prior studies have often overlooked the potential contribution of Blue Economy sectors, such as sustainable fisheries, marine tourism, and marine ecosystem conservation, in reducing carbon emissions. Moreover, they have tended to neglect how the energy transition from fossil fuels to renewable energy sources like solar, wind, and bioenergy can sustainably reduce CO2 emissions in the long term. Therefore, this study aims to fill this gap by comprehensively evaluating the role of the Blue Economy and renewable energy in reducing CO2 emissions, using the ARDL approach, which allows for simultaneous analysis of short-term and long-term relationships.

This study seeks to answer the primary question: How do the Blue Economy and energy transition affect CO2 emissions in Indonesia? Specifically, the study hypothesizes that implementing the Blue Economy and increasing the use of renewable energy will significantly reduce CO2 emissions in Indonesia. Furthermore, the study also considers the role of GDP as a control variable that could moderate the relationship between the Blue Economy, energy transition, and CO2 emissions. This study uses the ARDL approach to explore these strategies' short-term and long-term effects on CO2 emissions. The findings are expected to provide deeper insights into the effectiveness of the Blue Economy and energy transition in mitigating climate change in Indonesia, offering a solid foundation for formulating more sustainable environmental policies.

METHODS

This study aims to analyze the influence of the blue economy and energy transition on CO2 emissions in Indonesia, using the variables described in Table 1. The study uses secondary data spanning from 1990 to 2022. This time frame was selected to capture key policy changes and significant technological advancements in Indonesia's Blue Economy and energy transition sectors. However, there are potential limitations, such as the availability and accuracy of data, particularly for certain variables like aquaculture production. Historical data may be inconsistent due to varying data collection methods across years, potentially affecting the robustness of the findings. Addressing these data limitations is essential for a more comprehensive understanding of the study's implications.

The Autoregressive Distributed Lag (ARDL) model analysis technique is applied in this study. According to the concept presented by Gujarati and Porter, the ARDL model is used to analyze the influence of exogenous variables on endogenous variables over time, including the influence of past values of the dependent variable (Y) on current values of Y. Data was processed using EViews software, version 12.

The ARDL model was chosen based on the data characteristics, allowing for short-term and long-term relationships between independent and dependent variables. This model is flexible in handling variables with different integration orders (I(0) or I(1)) without requiring pre-cointegration testing. Model selection criteria involve stationarity testing and optimal lag selection based on information criteria such as AIC and SIC. The key coefficients in the ARDL model offer both short-term and long-term insights: short-term coefficients reflect the response of dependent variables to exogenous changes over time, while long-term coefficients reveal equilibrium relationships between variables over extended periods.

In analyzing the ARDL model, it is crucial to address potential endogeneity issues that could affect the accuracy of coefficient estimations. Endogeneity can arise if an independent variable correlates with the error term due to omitted variables, measurement errors, or a bidirectional causal relationship between variables. For instance, in this study, Blue Economy and energy transition variables may not be entirely exogenous to CO2 emissions due to complex reciprocal relationships or other factors that influence both. The study includes control variables, such as GDP, to mitigate this issue, as GDP is known to affect CO2 emissions significantly. Using GDP as a control variable helps reduce the risk of endogenous bias by capturing the effect of economic growth on emissions, leading to more accurate estimates and avoiding model specification errors.

Table 1. Variable operational

	Variable	Variable description	Data sources
Explained Variable	CO2	CO2 emissions (metric tons per capita)	World Bank
Explanatory Variable	AP	Aquaculture Production (AP)	World Bank
	REN	Renewable energy consumption (% of total final energy consumption)	World Bank
	IE	The energy intensity level of primary energy (MJ/$2017 PPP GDP)	World Bank
Control Variable	EG	GDP per capita (constant LCU)	World Bank

Aquaculture Production (AP) was selected due to its role in the blue economy, which has lower environmental impacts than traditional fishing methods. Renewable Energy Consumption (REN) is directly linked to CO2 emission reductions through cleaner energy sources. Energy Intensity (IE) measures the efficiency of energy use in the economy, providing insights into the effects of energy efficiency on carbon emissions, more specifically than simply assessing total energy consumption. GDP per capita (EG) is used as a control variable to account for the impact of economic development on CO2 emissions independently of energy and aquaculture factors, thereby improving the accuracy of the analysis.

In this study, the ARDL model is used to assess the effects of various factors on CO2 emissions. The main equation of the model is as follows:

$$CO2_t = \alpha_0 + \alpha_1 lnAP_t + \alpha_2 lnREN_t + \alpha_2 lnIE_t + \alpha_{i-j} X_{i-jt} + e_t \text{ ……………………(1)}$$

Where:

$CO2_t$ is CO2 emissions; AP is aquaculture production; REN is renewable energy consumption; IE is energy intensity; X_{i-jt} is the control variable, using economic growth proxied using GDP per capita, t represents the time series, e is the error term. The coefficients (α) measure the long-term impact of aquaculture production, renewable energy consumption, energy intensity, and economic growth on CO2 emissions, indicating how these variables affect emissions over time.

The ARDL model also captures both short-term and long-term effects through the following equation:

$$\begin{aligned}\Delta CO2_t = {} & \gamma_0 + \alpha_0 CO2_{t-1} + \alpha_1 lnAP_t + \alpha_2 lnREN_t + \alpha_3 IE_t + \alpha_4 lnEG_t + \\ & \textstyle\sum_{i=1}^{n} \rho_0 \, \Delta CO2_{t-1} + \sum_{i=1}^{n} \rho_1 \, \Delta lnAP_{t-1} + \sum_{i=1}^{n} \rho_2 \, \Delta lnREN_{t-1} + \\ & \textstyle\sum_{i=1}^{n} \rho_3 \, \Delta lnIE_{t-1} + \Delta lnEG_{t-1} \text{ ……………………………………………. (2)}\end{aligned}$$

In this model, $\Delta CO2_t$ represents the change in CO2 emissions from one period to the next. The coefficients $\alpha_{1,2,3,4}$ capture the short-term effects of aquaculture production, renewable energy consumption, energy intensity, and economic growth on CO2 emissions. The summation terms, $\sum_{i=1}^{n} \rho_0 \, \Delta CO2_{t-1}$ and similar terms account for the cumulative impact of past changes in these variables on current CO2 emissions. Intuitively, the α coefficients indicate how immediate changes in these variables affect CO2 emissions. In contrast, the ρ coefficients measure how variations from previous periods influence the current level of emissions, offering insight into the persistence of these effects over time.

Finally, the ARDL model incorporates the Error Correction Term (ECT) to assess the speed at which the system returns to equilibrium after deviations:

$$\Delta CO2_t = \vartheta_0 + \sum_{i=1}^{n} \gamma_{0i} \, \Delta CO2_{t-1} + \sum_{i=1}^{n} \gamma_{1i} \, \Delta lnAP_{t-1} + \sum_{i=1}^{n} \gamma_{2i} \, \Delta lnREN_{t-1} + \sum_{i=1}^{n} \gamma_{3i} \Delta IE_{t-1} + \sum_{i=1}^{n} \gamma_{4i} \Delta lnEG_{t-1} + \delta ect_{t-1} \quad \text{......................... (3)}$$

In this equation, δ represents the Error Correction Term (ECT) coefficient, which indicates the speed at which the system returns to equilibrium following deviations. A theoretically significant and negative δ value suggests that imbalances are corrected effectively, ensuring that short-term deviations are addressed and the system moves toward long-term equilibrium.

RESULTS AND DISCUSSION

Estimated results

The results of the unit root test, using both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) methods, showed that the dependent variable (CO2 emissions) and independent variables (lnAP, lnREN, IE, and lnEG) are all stationary at the first difference, or I(1) (Table 2). These variables require a first-difference transformation to remove trends and unit roots. Stationarity at the first difference (I(1)) indicates that the data exhibits a pattern that necessitates transformation to achieve stationarity. In the context of the ARDL model, this is not problematic since the ARDL method can handle variables with different integration orders simultaneously. Therefore, the ARDL model can estimate short-term and long-term relationships without requiring prior cointegration tests.

However, when interpreting the results, it is important to consider that stationary variables at the first difference reflect long-term trends. These trends influence the long-term coefficients in the model. In other words, although first-differenced stationary variables affect the estimation process, the ARDL model remains appropriate for analyzing the impact of the Blue Economy and energy transition on CO2 emissions.

Table 2. Unit root test results

Variable	Augmented Dickey-Fuller		Phillips-Perron	
	level	1st difference	level	1st difference
CO2	-1.3043	-4.8272***	-1.0269	-15.1333***
lnAP	-9.9119	-2.7934**	-0.5140	-2.7753**
lnREN	1.0029	-6.7238***	4.0636	-6.8596***
IE	0.7922	-2.4637**	-0.6653	-3.5234**
lnEG	-0.1430	-4.2107***	-0.1563	-4.1476***

*Note: ***, ** indicate significance at the 1% and 5% levels, respectively.*

The selection of the optimal lag length in this study was determined using the Akaike Information Criteria (AIC), as shown in Table 3. Based on Figure 2, the maximum lag length selected for the various variables is 3, 3, 0, 1, and 2. The use of AIC as a lag selection criterion is justified by its ability to identify parsimonious and efficient models, reducing model complexity while minimizing estimation errors. The model with the selected lag length provides the best balance between model fit and complexity.

The results of the ARDL bound test indicate that the estimated F-statistic exceeds the critical bounds for both I(0) and I(1), reaching 15.3826 at a 1% significance level. This suggests that the null hypothesis of no cointegration is rejected, confirming the presence of a cointegrating relationship in the model. The robustness of the results can be confirmed by testing alternative models with different lag lengths; if cointegration conclusions remain consistent, it strengthens the validity of the model. However, the model with the optimal lag length, based on AIC, is better suited to explain the long-term relationships between the variables in this study effectively and efficiently.

Table 3. ARDL Bound test cointegration results

ARDL Bound Test Model	**Lag selection**	**F-Stat**
$CO2_t = f(lnAP_t, lnREN_t, lnIE_t, lnEG_t)$	3, 3, 0, 1, 2	15.3826***
Critical Value Bounds		
Significance	**I(0)**	**I(1)**
10%	2.2	3.09
5%	2.56	3.49
2.5%	2.88	3.87
1%	3.29	4.37

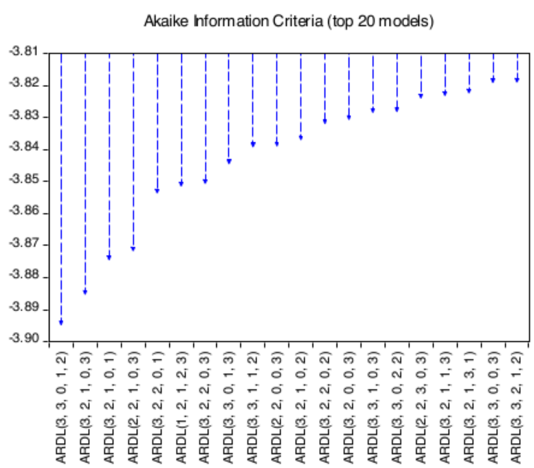

Figure 2. Akaike Information Criteria (Top 20 Model)

The results of the short- and long-term model estimates and the diagnostic tests are presented in Table 4. The short-term estimation indicates that the error correction term (ECT) has a negative coefficient of -9.8165, statistically significant at the 1% confidence level. This suggests that any imbalance in the model will be corrected, reaching equilibrium in approximately 9.81 years. Furthermore, the CO2 variable significantly affects lag 3 in the short term. The lnAP variable has a positive and significant coefficient at lag 3, indicating a delayed but significant influence. Meanwhile, lnREN exhibits a negative and significant impact at lag 0, suggesting an immediate effect, while IE has a positive and significant influence at lag 1. The control variable, lnEG, negatively affects CO2 at lag 2 in the short term.

Table 4. Long and short-run ARDL estimation

Dependent variable = CO_2			
Long-run			
Variable	**Coef.**	**Std. Error**	**t-Stat.**
C	-5.6139***	1.2693	-4.4226
lnAP	-0.0375*	0.0196	-1.9135
lnREN	-0.5389***	0.1418	8.0250
IE	0.9091***	0.0717	12.6736
lnEG	1.1386	0.0196	1.9135
Short-run			
Δ(CO2)	0.2186**	0.0878	2.4882
Δ(lnAP)	0.1942**	0.0081	2.2028
Δ(lnREN)	-0.9423***	0.1553	-6.0659
Δ(lnIE)	0.8837***	0.2837	3.1143
Δ(lnEG)	-0.7609**	0.2828	-2.6904
ECTt-1	-9.8165***	2.6761	-3.6681
Diagnostic test			
Test	**F-stat.**		**Prob.**
LM test			
Normality test	1.9758		0.5189
Heteroscedasticity test	1.3983		0.0823
Ramsey RESET test	8.2891		0.1150

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

In the long term, lnAP and lnREN have negative and significant coefficients, indicating their negative impact on CO2 emissions. Conversely, IE has a positive and significant influence, suggesting increased energy intensity is associated with higher CO2 emissions. The positive coefficient for IE implies that although energy efficiency may improve, it can inadvertently lead to increased CO2 emissions unless complemented by greater renewable energy use. Therefore, policies focusing on energy efficiency must also prioritize expanding renewable energy technologies to mitigate potential negative effects on carbon emissions. The control variable lnEG, shows a positive but statistically insignificant impact on CO2 emissions in the long term, suggesting that economic growth alone may not substantially influence CO2 emissions unless accompanied by structural changes in energy consumption and production.

Table 4 also includes results from several diagnostic tests, confirming the validity of the research model. The normality test (p-value = 0.5189) indicates that the residuals are normally distributed. The heteroscedasticity test (p-value = 0.0823) suggests that the residuals exhibit constant variance, meaning no heteroscedasticity issue exists. The Ramsey RESET test (p-value = 0.1150) shows no significant specification errors in the model. These diagnostic results confirm that the model is robust and reliable for further analysis.

The stability of the ARDL model was assessed using the CUSUM and CUSUM of Squares tests (Figure 3). The results show that the CUSUM and CUSUM of Squares lines remain within the 5% significance boundaries throughout the period, indicating that the model is stable and does not experience significant structural changes over time. This confirms the long-term stability of the model's estimated parameters, ensuring the reliability of the results.

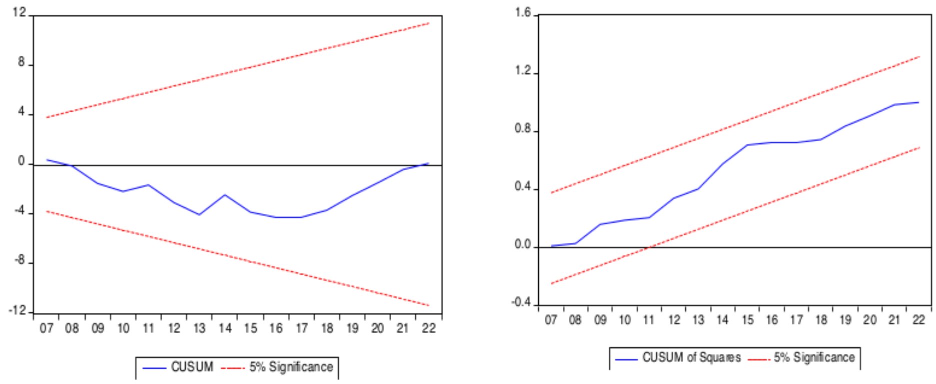

Figure 3. Cumulative sum of recursive residuals (CUSUM)

Discussion

The discussion of the results highlights the varying effects of aquaculture production, renewable energy consumption, energy intensity, and economic growth on CO2 emissions in Indonesia, both in the short and long term.

In the short term, aquaculture production positively and significantly impacts CO2 emissions. This is largely due to the intensification of production, which demands more energy and resources. Energy is required to maintain aquaculture infrastructure, environmental conditions, and waste management systems. Operations and transportation often rely on fossil fuels, further contributing to emissions (Little et al., 2017). Additionally, unsustainable practices, such as using chemical fertilizers, antibiotics, and illegal fishing for feed, increase emissions (Boyd et al., 2020). Overfishing disrupts ecosystems and affects the carbon cycle in aquatic environments, leading to a higher carbon footprint. These findings align with previous studies (Badîrcea et al., 2021; Bhattacharya & Dash, 2020).

However, in the long term, the relationship between aquaculture production and CO2 emissions becomes more complex. The environmental impact can be reduced as the industry moves towards sustainable and efficient practices. For example, adopting environmentally friendly management practices, such as more efficient feed use, reduced chemical reliance, and stricter regulations on illegal fishing, can help lower the industry's carbon footprint. Investments in energy-efficient technologies and a transition to renewable energy further mitigate CO2 emissions. The European Union's investments in aquaculture technology, including more efficient marine cage systems and recirculating aquaculture systems, serve as a valuable example of how these changes can lead to reduced environmental impacts (Bostock et al., 2016). Thus, while aquaculture may increase emissions in the short term, long-term sustainable strategies can significantly decrease its carbon footprint.

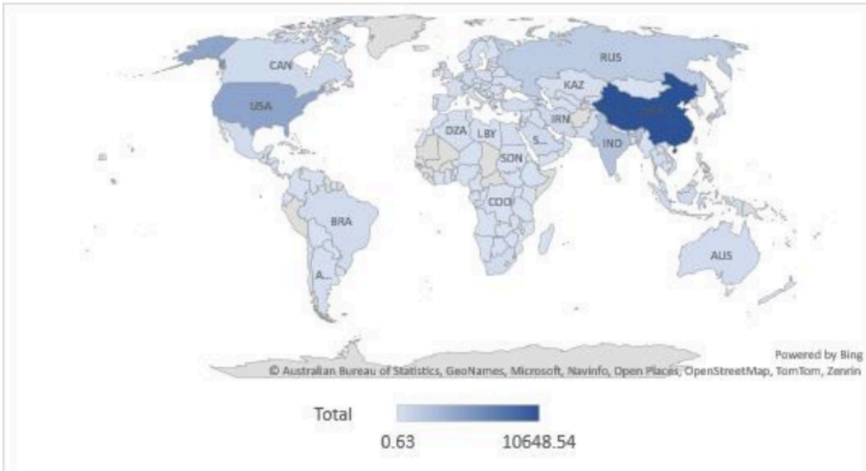

Figure 4. CO2 emissions from fuel combustion, regional ranking, 2021
Source: International Energy Agency, data processed (2024)

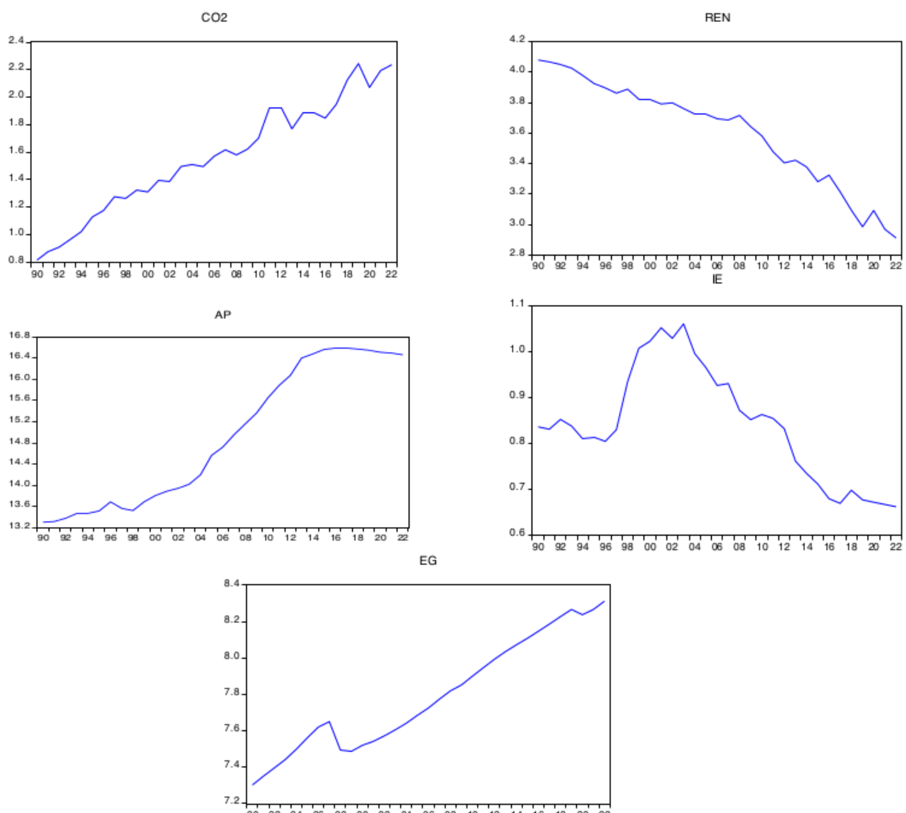

Figure 5. Movement of CO2 emission variables, aquaculture production, renewable energy consumption, energy intensity, economic growth

Renewable energy consumption negatively and significantly influences CO2 emissions in the short and long term. This underscores the importance of increasing renewable energy usage to lower emissions. In the short term, technologies such as solar, wind, and biomass reduce dependence on fossil fuels, directly reducing greenhouse gas emissions (Idroes et al., 2024; Saudi et al., 2019). In the long term, renewable energy promotes greater efficiency through improvements in energy infrastructure and the development of sustainable green technologies. Government policies, such as fiscal incentives and green energy projects, are critical in accelerating renewable energy adoption (Abdmouleh et al., 2015; Abolhosseini & Heshmati, 2014).

Despite Indonesia's significant greenhouse gas emissions, mainly from deforestation and fossil fuel reliance, the growing use of renewable energy presents an opportunity to significantly lower emissions. Renewable energy could reduce Indonesia's reliance on coal and petroleum, the primary energy sector emissions sources (Rahman et al., 2023b). However, challenges such as low investment in the energy sector, technological hurdles, and institutional barriers slow the transition to renewable energy. The government has set ambitious goals to increase renewable energy usage to 23% by 2025 and 31% by 2050, but achieving these targets will require clear policies, mandates, and significant investment (Raihan et al., 2023).

Energy intensity positively and significantly influences CO2 emissions in the short and long term. Reducing energy intensity, which measures the energy needed to produce one unit of economic output, is associated with decreased CO2 emissions. In the short term, this can be achieved by improving energy efficiency in industrial processes, transportation, and household use, directly reducing fossil fuel consumption and emissions (Fais et al., 2016). Long-term reductions in energy intensity can be achieved through improvements in energy infrastructure, the adoption of low-carbon technologies, and policies that promote energy conservation (Shahbaz et al., 2020; Danish et al., 2020).

Indonesia's energy intensity is lower than that of neighboring countries such as Vietnam and Thailand but still higher than Singapore and the Philippines (Santika et al., 2020). The National Energy Policy targets a 1% annual reduction in energy intensity, with initiatives promoting energy efficiency in the private and public sectors (Nurcahyanto et al., 2020). As energy efficiency improves, CO2 emissions can decrease without negatively impacting economic growth, making energy intensity a key area for Indonesia's climate change mitigation strategies.

Economic growth positively and significantly affects CO2 emissions in the short and long term. As economic activity increases, so do energy consumption and emissions. In the short term, industrial production, trade, and transportation are typically accompanied by increased fossil fuel use, leading to higher CO2 emissions (Mikayilov et al., 2018; Aye & Edoja, 2017). Long-term economic growth sustains this trend, with growing energy demands across sectors. Despite Indonesia's efforts to adopt renewable energy and improve energy efficiency, economic growth continues to drive up CO2 emissions.

This pattern is similar in Southeast Asian countries, such as Vietnam and Thailand, where industrialization and economic growth have increased emissions (Quy et al., 2024). However, Thailand's adoption of low-carbon technologies and fiscal policies promoting renewable energy has helped reduce its environmental impact (Chien et al., 2023). Vietnam's shift towards sustainable aquaculture has also reduced long-term CO2 emissions despite initial increases from production intensification (Henriksson et al., 2018). Indonesia can learn from these experiences by further integrating green policies, investing in renewable technologies, and promoting energy efficiency to achieve sustainable economic growth without exacerbating CO2 emissions.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study reveals that aquaculture production in Indonesia has varying impacts on CO2 emissions in the short and long term. In the short term, increasing aquaculture production tends to reduce CO2 emissions due to initial efficiency gains and using environmentally friendly technology. However, in the long term, intensified production and unsustainable management practices contribute to more complex effects, potentially increasing emissions. Furthermore, renewable energy consumption in Indonesia has a negative and significant influence on CO2 emissions, both in the short and long term, highlighting the substantial role renewable energy plays in reducing emissions. Conversely, energy intensity positively influences CO2 emissions, indicating that energy efficiency, infrastructure, and technology improvements are necessary to reduce emissions. Lastly, economic growth positively affects CO2 emissions, as increased economic activity drives higher energy consumption and fossil fuel use.

This study shows that aquaculture production in Indonesia has different impacts on CO2 emissions in the short and long term; where in the short term, increasing aquaculture production reduces CO2 emissions thanks to initial efficiency and environmentally friendly technology, while in the long term, the impact becomes more complex due to intensified production and unsustainable management practices. In addition, renewable energy consumption in Indonesia shows a negative and significant influence on CO2 emissions in both the short and long term, indicating that increasing the use of renewable energy can significantly reduce CO2 emissions. In contrast, energy intensity positively influences CO2 emissions, meaning that a decrease in energy intensity correlates with a decrease in CO2 emissions. This can be achieved through an increase in energy efficiency through infrastructure improvement, adoption of efficient technology, and energy-saving policies. Economic growth in Indonesia also has a positive and significant effect on CO2 emissions, where increased economic activity increases CO2 emissions due to increased energy consumption and the use of fossil fuels.

Recommendations

A comprehensive and sustainable strategy is necessary to reduce CO2 emissions while ensuring sustainable economic growth in Indonesia. In the aquaculture sector, it is crucial to implement more environmentally friendly management practices, such as using sustainable feeds, reducing chemical usage, and enforcing stricter monitoring of illegal fishing. Investments in green technologies are also recommended to improve production efficiency without raising CO2 emissions.

Investing in solar, wind, and biomass energy should expand renewable energy consumption. This can be achieved through government policies that provide fiscal incentives and support green energy projects. Moreover, energy efficiency should be prioritized across industrial, transportation, and household sectors by adopting efficient technologies and developing better energy infrastructure.

However, implementing these policies may encounter political resistance and financial constraints. Mitigation strategies should focus on overcoming these challenges by increasing public awareness and support for environmental policies, strengthening institutional capacity for effective policy implementation, and creating innovative funding schemes to facilitate investments in green technologies and renewable energy. The government should also develop a regulatory framework that incentivizes companies and communities to adopt greener practices. By integrating these measures, Indonesia can more effectively balance economic growth and environmental sustainability.

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