Decomposition of air pollution in Indonesia

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Abstract. The impact of environmental damage and pollution on health and the economy has become a global concern in recent years, including in Indonesia. In Indonesia, the average number of deaths caused by air pollution is 123,000 yearly, and a decrease in life expectancy by 1.4 - 2.4 years by WHO guidelines. This study investigates the decomposition of air pollution (CO^2 emissions) in Indonesia from 1995 to 2022. We imposed structural variables comprising urbanization, liberalization, and fossil-based energy. We also associate renewable energy and environmental policy stringency index to describe the decarbonization skeleton. This study uses a dynamic autoregressive distributed approach to examine the interaction between independent variables and carbon emission levels. The results show a diverse influence of urbanization, liberalization, and fossil fuel when associated with skeleton variables that impact the pattern of pollution shaping. Renewable energy is the most critical factor in promoting inclusive decarbonization, while institutional quality is central to generating robust environmental policies. The implication is that a firm commitment is needed to achieve carbon neutrality through clean technology innovation and renewable energy.

1 Introduction

Indonesia's carbon emissions have grown relatively rapidly and are of significant concern for the environment and health. CO_2 emissions grew 18.34 percent in 2022, the largest in the last two decades. This leads to a sensible increase in greenhouse gas (GHG) concentrations in the atmosphere, resulting in a natural greenhouse effect that is harmful to the environment. Greenhouse gas (GHG) emissions have become a global issue due to increased CO_2 in the atmosphere [1]. Based on Global Carbon Budget data, in 2023, Indonesia produced 729 $MtCO_2$ and ranked sixth globally, below Japan. This phenomenon is due to natural and anthropogenic factors, which anthropogenic factors such as energy sectors (electricity) and industries contribute 70 percent to the establishment of carbon emissions in this region. As a primary input and driver of economic growth, 83.44 percent of Indonesia's energy consumption derives from fossil fuels (coal, natural gas, and oil), so the government faces a tough challenge in reducing carbon emissions. This symptom is inseparable from development strategies based on sustainable economic growth or environmentally destructive growth.

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The Indonesian government has committed to reducing carbon dioxide emissions by the Paris Agreement (United et al. on Climate Change/ UNFCCC) signed on April 22, 2016. The treaty aims to defend against the rise in global temperature in this century below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit temperature rise to below 1.5 degrees Celsius. Indonesia's commitments include: Nationally Determined Contribution (NDC) to reduce greenhouse gas emissions by 31.89% in 2030, LTS-LCCR 2050, which is to achieve carbon neutrality or even a net carbon sink for the FOLU sector by 2030, Net-Zero Emissions in 2060, and Nusantara Net Zero Strategy 2045. The actions are, (i) policies on Feed-in tariffs to encourage renewable energy investment, (ii) renewable energy priority for remote and outermost areas, (iii) substitution of diesel power plants within three years, (iv) override of coal as an alternative power plant, and (v) harmonization of the 2024 State Budget (APBN) to achieve net-zero emissions. In addition, the government also promulgated the use of green technology for the energy sector, energy efficiency, scaling the use of carbon fuels, and promoting clean energy markets [3], including implementing a carbon tax through the 'Cap-and-Tax' scheme [4].

However, Indonesia's low-carbon development target is an ambitious and forced project. This is due to several factors. First, the abundant endowment of coal mining areas reached 11.20 million hectares and produced 687.4 Mt (ranked third in the world) in 2022 [5]. It causes the energy sector to rely on coal at 74.28 percent and 21.35 percent on oil and natural gas. This repression implies that Indonesia's energy sector is based on dirty energy, which is coherent with carbon emissions. In addition, Indonesia's economic growth still relies on polluting product sectors such as the extraction and export of coal, crude oil, and palm oil. Indonesia is also a pollution haven for several industries, such as chemicals, pulp, and paper [6], so Indonesia has a comparative advantage for polluting products. Second, from the perspective of institutional quality, policies on low-carbon emissions are still overlapping, and there is dissonance between the central and local governments, resulting in low political commitment and awareness [7]. It causes the disintegration of programs and policies between local and central government, including horizontal and vertical authority conflicts between government levels [8], which leads to the dominance of sectoral egos and both sides running independently. Policy disintegration leads to misallocating resources between government structures, resulting in ineffective objectives, implementation, and enforcement for the community [9]. Therefore, Indonesia needs to develop a centralized and low-carbon emission policy strategy as a priority development program towards zero-carbon. Third, technology and innovation barriers are related to the cost of absorption of environmentally friendly technologies. For example, carbon capture and storage (CCS) technology costs the equivalent of \$35-\$60 to treat one ton of CO_2, not including the cost of procurement. In addition, technological development and innovations to transform dirty energy into renewable energy are also complex challenges. Finally, low-carbon policies must involve stakeholders and all elements of society, but the reluctance and behavior of people indifferent to the environment is a challenge to implementing this policy. Social and cultural values that tend to be strong in each region make them 'Not in My Backyard' and feel comfortable with current conditions [8]. In addition, there is an assumption that this is the 'authority and obligation of the government,' so people tend to ignore the policy. It is also supported by the availability of competent, skilled labor, especially in this field.

Previous studies have examined the formation of carbon emissions in Indonesia from various perspectives; Indonesia's liberalization contributes positively to carbon emissions and causes natural resource depletion in the long run [10]. Because Indonesia's exports are based on primary products, exploiting resources causes environmental damage. It is also in line with the opinion of [11] and [12] that Indonesia's liberalization promotes resource depletion and natural damage. However, this contradicts [13] that trade openness can reduce carbon emissions and encourage a better environment. Market pressures and global policies encourage domestic industries to allocate resources efficiently by absorbing clean technology. Clean technology creates sustainable production and improves environmental quality.

Energy consumption is one of the main factors related to carbon emissions. Indonesia's fossil fuel consumption will worsen environmental quality [14], especially for coal and natural gas [15]. It is inseparable because Indonesia has a comparative advantage in endowment, namely coal, natural gas, and oil mining areas, reaching 97.77 million hectares. Renewable energy is an innovative solution to conventional energy. With abundant natural resources, Indonesia has great potential to develop renewable energy in the form of geothermal, water, wind, and solar power [16] so that Indonesia can design policy models to promote renewable energy [14]. However, renewable energy development in Indonesia still faces many challenges, namely technological limitations and sizeable initial investment costs [17], and the government's courage to implement an energy mix remains [18]. Indonesia must urgently 'get out of its comfort zone' through collaborative innovation and clean technology to safeguard the environment and sustainable development.

The concentration of industry drives people to move to urban areas, increasing population density. Indonesia's urbanization rate will reach 58.57 by 2023, increasing pollution in urban areas. Some empirical evidence shows that urbanization is one of the causes of high carbon emissions in Indonesia [19], [20], [21], and [22]. However, [23] and [24] reject this axiom and argue that urbanization improves environmental quality in the long run and supports ecological modernization theory. It is consistent with the environmental Kuznets curve, where environmental quality improves in the post-industrial economy phase due to higher living standards.

Indonesia's carbon emissions are integral to its environmental policy regime. In the long run, economic growth and complexity contribute to reducing carbon emissions through technology transmission in the mining sector [25], even though technology in the sector tends to be constant in the last few decades. It implies that vigorous environmental policy and government commitment are central to reducing carbon emissions in Indonesia. This study aims to investigate the decomposition of air pollution, especially carbon emissions, in Indonesia by combining various economic (trade liberalization and energy consumption), social (urbanization), and policy (environmental policy stringency index) variables. We employ dynamic simulated autoregressive distributed lag (DSARDL) as the interpretation model. The contributions of this study are as follows: (i) We model the structural modifiers, namely economic, social, and policy, in one analytical framework simultaneously. It aims to produce a comprehensive model of carbon emission decomposition in Indonesia. (ii) we interact EPS with other variables to assess whether environmental policies can strengthen or weaken economic and social performance regarding carbon emissions in Indonesia. (iii) we also document all three variables in the long and short term to compare whether there is a difference in the performance of each carbon emission decomposition variable in Indonesia over different periods.

2 Methods

1.1 Data and Source

The studies on carbon emissions are debatable due to divergent factors in several contexts. This study investigates the decomposition of carbon emissions in Indonesia. We generate three structural variables: urbanization, energy consumption (fossil and renewable), trade openness, and environmental policy stringency index. We rely on the 1995-2022 time series data from the respective databases of the UN Population Division, the US Energy Information

Administration (EIA), the World Bank, and the Organization for Economic Co-operation and Development (OECD). The dependent variable is CO_2 carbon emissions from the Global Carbon Budget database in a million tons (Mt).

Moreover, we executed the unit root test before conducting the model test. This aims to identify the presence of stationary (non-stationary) and order of integration [I(0), I(1), I(2),.....I(n)] in the model. In this study, we use the Augmented Dickey-Fuller approach [26].

1.2 Model Specification

The CO_2 emission model generally uses the standard Marshallian demand function approach [27] by combining various independent variables at time t. It is written as follows:

$$CO_{2t} = f\,(Urb_t, EnC_{Ft}, EnC_{Rt}, Lib_t, EPS_t \ldots\ldots\ldots\ldots\ldots (1)$$

where CO_2 is carbon emission, *EnC* is energy consumption (*F* and *R* are fossil and renewable, respectively), *Lib* is trade openness, *EPS* is environmental policy stringency index, and t is time.

Furthermore, equation (1) is rewritten into an ARDL model as follows:

$$\begin{aligned}\Delta CO_2 = {} & \vartheta_0 + \vartheta_1 CO_{2t-1} + \vartheta_2 Urb_{t-1} + \vartheta_3 EnC_{Ft-1} + \vartheta_4 EnC_{Rt-1} + \vartheta_5 Lib_{t-1} + \vartheta_6 EPS_{t-1} \\ & + \sum_{i=1}^{p} \theta_1 \Delta CO_{2t-i} + \sum_{i=0}^{q} \theta_2 Urb_{t-1} + \sum_{i=0}^{q} \theta_3 EnC_{Ft-1} + \sum_{i=0}^{q} \theta_4 EnC_{Rt-1} \\ & + \sum_{i=0}^{q} \theta_5 Lib_{t-1} + \sum_{i=0}^{q} \theta_6 EPS_{t-1} + \varepsilon_t \ \ldots\ldots\ldots\ldots\ldots (2)\end{aligned}$$

where Δ is the first difference operator, and q is the optimal lag. Meanwhile, ϑ is the parameter of independent and dependent variables in lag, and θ indicates the constant of short-term variables. To test the existence of cointegration in the model, Wald test is conducted with hypothesis criteria H0: $\vartheta 1 = \vartheta 2 = \vartheta 3 = \vartheta 4 = \vartheta 5 = 0$ and H0: $\vartheta 1 \neq \vartheta 2 \neq \vartheta 3 \neq \vartheta 4 \neq \vartheta 5 \neq 0$.

Furthermore, we proceed with the dynamic ARDL method to avoid endogeneity problems that may lead to spurious regression. For this reason, it must be ensured that the dependent variable is stationary in the first difference [I(1)], the regressor has no integration, and the estimation is in error correction form [28]. In addition, the dynamic model is more precise in predicting the actual change of each variable with the assumption that other variables in the equation are constant [25]. Moreover, we also interact with the policy (EPS) regarding urbanization, industrial performance, and energy consumption variables. We also apply the Bounds test, residual diagnostics, and stability test to test the robustness of the model used.

3 Result and Discussion

Our results confirm that all variables are cointegrated in the long run with structural breaks in the series. Table 1 presents the summary of the unit root test results related to the order of integration using the Augmented Dickey-Fuller approach (ADF). This model is used because it can incorporate lagged differences into the regression equation, thus accounting for potential autocorrelation and improving the accuracy of the unit root test. The unit root test is a random walk and asymptotic normality as the sample increases but still yields robust conclusions for larger data sets and is consistent across time. The spectral density assumption encourages a decrease in the asymptotic distribution under the null hypothesis of a unit root, thus promoting high accuracy in the test according to the dynamics of the underlying data.

Table 1. Order of Integration (ADF-test)

At level I(0)

	CO_2	EnC_F	EPS	Urb	Lib	EnC_R
Intercept	-0.7240	-0.5223	-0.3539	-1.4695	-0.9661	1.5476
Intercept & trend	-5.1829***	-3.3235*	-0.9859	-1.8434	-4.7154**	-1.2405
Without intercept & trend	2.8902	3.6079	0.8804	-3.3009***	-0.6247	-2.0510**

At first difference I(1)

	ΔCO_2	ΔEnC_F	ΔEPS	ΔUrb	ΔLib	ΔEnC_R
Intercept	-7.7624***	-6.8907***	-5.1684***	-4.9335***	-5.3183***	-5.9052***
Intercept & trend	-7.5312***	-6.5820***	-3.6461***	-5.0264***	-5.2525***	-6.4911***
Without intercept & trend	-5.5530***	-0.5037*	-4.8915***	-3.9234***	-5.3978***	-4.7157***

Note: ***, **, and * designate significant at 1%, 5%, and 10%, respectively.

Table 2. Estimation Results of Short- and Long-Term CO_2 Decomposition

Short-run

Variable	Coefficient	t-Statistic
$\Delta CO_2(-1)$	-0.3442	-2.1365
ΔEnC_F	0.8251***	4.3534
ΔESP	0.1614**	2.566
ΔUrb	-0.1618**	-3.2864
ΔLib	-0.0005	-0.4594
ΔEnC_R	-0.1122*	-1.9122

Long-run model

Variable	Model 1	Model 2	Model 3	Model 4
EnC_F	0.614(3.604)***	0.435(2.693)***	4.806(2.750)*	0.046(0.116)
EnC_R	-0.084(-1.972)*	-0.217(-2.940)***	-0.802(-2.656)*	-0.061(-0.527)
EPS	0.120(2.781)**	0.392(2.101)**	-23.039(-2.436)*	-7.510(-3.628)*
Lib	-0.001(-0.446)	-0.002(-2.501)**	-0.001(-0.385)	-0.003(-1.975
Urb	-0.120(-2.843)**	-0.110(-3.605)***	-0.482(-2.982)**	-0.216(-4.449)**
EPS^2		-0.266(-2.756)***	-3.074(-2.454)*	-1.401(-4.140)*
$EPS\text{^}EnC_F$			0.532(2.465)*	
EPS^Urb				5.249(3.913)*

Note: ***, **, and * designate significant at 1%, 5%, and 10%, respectively.

Based on the ADF test, all variables reject the null hypothesis individually and jointly, meaning there is no unit root. Variable tests fulfill the assumption of asymptotic normality in the first difference. It indicates that the variable data set is stationary at the I(1) degree of integration both for intercept, intercept, and trend and without intercept and trend, so it is feasible to conduct Johansen cointegration test and model testing to build the ARDL model.

In the short term, the relationship between energy consumption and carbon emissions rejects the null hypothesis at α level below 1 percent. It is suggested that a 1 percent increase in fossil energy consumption will lead to a 0.83 percent thickening of carbon emissions. This finding is in concordance with [14] and [15], where both variables have a significant and positive relationship. While renewable energy significantly negatively affects the formation of carbon emissions, an increase in renewable energy productivity by 1 percent cuts carbon emissions by 0.11 percent. This finding confirms [20] that clean energy contributes to reducing carbon emissions (GHG) by global agreements.

This result is coherent with the long term, where fossil-based energy drives the thickening of carbon emissions in nature and vice versa for renewable energy. The only difference lies in the magnitude of the coefficient between the two periods, where the short- term coefficient is larger than the long-term one. This impression agrees with the global demands of the Paris Agreement on low-carbon emissions towards zero carbon by 2060. The study suggests that Indonesia depends on dirty energy due to its abundant resource endowment. No doubt, fossil fuel is the national energy source and the sixth most significant contributor to emissions globally. This dependence will encourage over-exploitation of natural resources, leading to their depletion. This means thwarting sustainable development due to the stagnation of national fuel energy-base economic development in the long run. Therefore, developing renewable energy infrastructure must be a national priority in encouraging the transition from dirty to clean energy. Indonesia has developed several renewable energy infrastructures with a reasonably broad scope, but budget constraints and public awareness are substantial challenges to the development of this program. In addition, Indonesia's relatively fixed and even increasing production of fossil energy sources obstructs clean energy development. Renewable energy is more expensive than fossil energy due to regulated prices, resulting in limited purchasing power and delays in renewable energy development.

This study also explores the strength of environmental policy and the environmental policy stringency index on environmental degradation in Indonesia. Based on the empirical results (model 1), without including the square of the policy variable (EPS), it shows that environmental policies participate in carbon emissions. The estimation presented that environmental policy drives the increase of carbon emissions in Indonesia both in the short and long term, with coefficients of 0.83 and 0.12, respectively. This is related to the relatively low/ineffective level of environmental policy stringency. Indonesia tends to make strict environmental policies because it has a low EPS index and a high polluter.

To avoid a non-monotonic (biased) relationship in the environmental policy-degradation model, we include the square of the policy variable (EPS) in the estimation. Model 2 is the estimation result with the square of environmental policy (EPS_2); the result is that EPS^2 is significantly negative and shows an inverted U-shaped or concave relationship between the two variables. This implies that, at the beginning of the implementation of environmental policy tightening, environmental degradation is caused, but after the threshold point is reached, the tightening of the environmental policy erodes carbon emissions. This indicates that more robust environmental policies will encourage the retrogression of carbon pollution in the long run. This finding is consistent with [29] finding of an inverted U-shaped relationship in Indonesia and BRIICTS countries, [30] stated that there is a positive relationship between EPS and ecological footprints in China, [31] also detected the same pattern in G7 countries, and [32] in sub- Saharan Africa. These results also confirm the Environmental Kuznets Curve (EKC) hypothesis, which is the relationship between vigorous environmental policies versus carbon emissions.

Urbanization has a significant and negative influence on the level of CO_2 pollution in Indonesia, with coefficients of 0.16 (short term) and 0.12 (long term). This finding supports previous results from [23] and [24] in different contexts. Theoretically, this finding legitimizes the inverted U-shaped Environmental Kuznets Curve (EKC), especially in the third phase of economic security. Urban concentration in metropolitan cities will initially cause pollution and environmental damage, but after reaching a specific limit, urban agglomeration will become self-medicating when opinions are high and demand for quality of life increases. Higher living standards encourage people to live healthier lives, meaning people are willing to increase spending to 'buy' a cleaner and healthier environment.

Meanwhile, trade liberalization has no impact on environmental pollution for both periods. However, trade liberalization will create a better ecological environment associated with squared long-term policy variables (EPS^2). This finding aligns with [13] that trade liberalization will lead to environmental improvement through several transmissions, especially technology transfer from developed countries. This suggests that the engineering effects of free trade will mask the scale effect of free trade. It is in response to global demand and stricter regulation in production and distribution. Trade liberalization stimulates the transition and adoption of clean technologies, creating a better environment and achieving sustainable development.

4 Conclusion

Empirical evidence confirms that the consumption of fossil-based energy is the main contributor to the shaping of CO_2 emissions, while renewable energy erodes CO_2 in all periods. The environmental policy strength variable (EPS) positively affects carbon emissions, but in the long run, EPS squared (EPS^2) causes a weakening of CO_2 emission. Environmental policy stringency thickens CO_2 emissions in the short term and reveals an inverted U-shaped relationship. Weak environmental policy stringency causes the government to accelerate massive low-carbon policymaking. Urbanization has a negative significant association with carbon pollution. Urbanization promotes environmental improvement by developing clean and conservative urban planning, adequate health services, transportation system innovation, energy efficiency, and sufficient essential services. Trade liberalization significantly negatively affects CO_2 pollution when associated with long-term policy squaring (EPS^2). Liberalization stimulates technology transfer from developed countries and a global environmental nudge.

This research implies that carbon emissions can be reduced by transitioning from dirty energy to clean energy driven by strong environmental policies. Governments should encourage accelerating the adoption of clean technology and the development of renewable energy infrastructure as a national development priority. Vigorous and centralized environmental policies are an effective strategy to avoid incoherence between government agencies and strict enforcement for lawbreakers. It aims to achieve zero carbon in 2060 as targeted.

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