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The Role of Economic Sectors on Carbon Emissions in Indonesia

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Abstract: Human activities' negative impacts are thought to be causing increasing environmental damage and ongoing global climate change. This study aims to evaluate the impact of economic activity, particularly activities in the agriculture and industry sectors, on carbon dioxide emissions based on the STIRPAT model approach. Focusing on Indonesia and using time series data from the World Bank from 1990-2022, this research uses the Autoregressive Distributed Lag - Error Correction Model (ARDL-ECM) method to capture the long-term and short-term relationship. The results show that the STIRPAT model is robust in modelling the impact of economic activities on environmental degradation. The variable of interest of this research is renewable energy consumption, which plays a proxy in the technology and eases carbon emissions in the manufacturing and service sectors. So that, by increasing renewable energy consumption helps reduce carbon emissions in both the manufacturing and service sectors.

Keywords: STIRPAT, Carbon Emissions, Economic Sector, ARDL-ECM

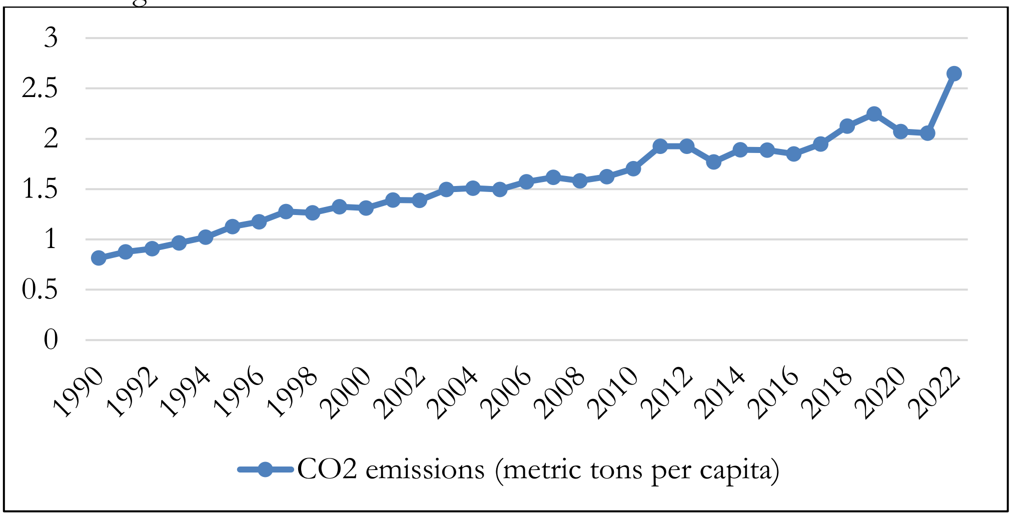
Introduction

Indonesia is among the top 10 carbon emitters in the world, according to a report by scientists at the Global Carbon Project. The amount of carbon produced by Indonesia in 2022 reached 729 million tons of carbon dioxide. This figure increased by 18.3 percent from the previous year and is higher than in other countries (Global Carbon Atlas, 2023). Using fossil energy, especially coal, is Indonesia's leading cause of increased emissions. In addition, deforestation and land conversion are other causes to emissions (Lai, et all, 2016).

As the world's seventh largest emitter, Indonesia's efforts to reduce carbon emissions will be critical to addressing the climate problem. Effective mitigation measures will affect the lives of Indonesia's 275 million current and future generations. According to the Asian Development Bank (2021), Indonesia ranks third in high climate risk due to flooding and extreme heat. This is because 65 percent of the population lives in coastal areas, making Indonesia more vulnerable. In addition to increasing the risk of natural disasters, the 2020 Adaptation Nationally Determined Contributions (NDC) roadmap estimates that climate change could cost the country's economic sector 0.66-3.45 percent of gross domestic product by 2030. To overcome this, the Indonesian government has released policies, such as a carbon tax. In 2021, Indonesia introduced a carbon tax as part of the Harmonized Tax Law (Law 7/2021). This policy aims to tax entities exceeding specific emission limits, starting with coal-fired power plants in 2022. The tax rate is set at IDR 30 per kilogram of CO_2 equivalent. Meanwhile, a few moments before the carbon tax, the Indonesian government released Presidential Regulation No. 55 of 2019 to accelerate the adoption of electric vehicles. It includes fiscal incentives, charging infrastructure development, and local EV manufacturing, and many more

Aware of the challenges of the climate crisis, Indonesia ratified the Paris Agreement by enacting Law Number 16 of 2016 concerning Ratification of the Paris Agreement to the United Nations Framework Convention on Climate Change. Furthermore, in the 2022 NDC target, Indonesia is committed to reducing greenhouse gas emissions by 31.89 percent with its capabilities, and by 2030, it can achieve a target of 43.20 percent with international support in funding, technology, and capacity building.

Figure 1. **Carbon Dioxide Emissions in Indonesia 1990-2022**



Source: World Development Indicators (2023)

Figure 1 shows that carbon dioxide emissions in Indonesia had increased, as seen from the movement of the carbon dioxide emissions graph in 1990 of 0.814 metric tons per capita, which then fluctuated every year until 2022 when they reached 2.646 metric tons per capita. The increase in the amount of carbon dioxide emissions indicates that climate change has occurred, which has resulted in a decrease in environmental quality, resulting in environmental degradation in Indonesia. Widyawati et al. (2021) revealed that the high urban population impacts environmental degradation, especially on increasing carbon emissions. This is because the high level of urban population causes daily activities that use energy to drive carbon dioxide emissions to increase.

Various efforts are made to reduce carbon dioxide emissions to meet the desired target. These efforts can be known through the aspects that cause carbon dioxide emissions by analyzing emission phenomena based on aspects of demographics (population), economic activity, and technology. The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) has been widely validated and applied in environmental research globally, making it a reliable and trusted tool. This model is appropriate model to be applied to various economic and environmental systems because it is simple and systematic (Dietz & Rosa, 1997). This is because the flexibility of STIRPAT model. Compare to IPAT model that deterministic, STIRPAT incorporates statistical methods, enabling researchers to measure the relative contributions of factors like population, affluence, and technology. The STIRPAT model can be tailored to address specific research purposes by adding or modifying variables as long as we can find suitable proxy for variables.

In essence, environmental management not only regulates the environment but also regulates and controls various human activities so that they take place and impact the limits and limitations of the environment to support them (Samadi, 2006). In the context of Indonesia, environmental management has several specific functions and strategies tailored to the country's unique challenges, such as high biodiversity, rapid urbanization, and extensive natural resources. However, there still gap in regulation and implementation. Despite strong regulations, implementation and enforcement remain inconsistent, often due to corruption and lack of resources (Abdurrachman, et all, 2021). Moreover, rapid economic growth and infrastructure development often take precedence over environmental considerations. This prioritization leads to environmental degradation, as economic interests overshadow the need for conservation (Susanto et all, 2024).

An increasing population can lead to high carbon dioxide emissions because many people can increase the utilization of natural resources such as forest products, air, and land. This leads to environmental degradation, such as deforestation, air and soil pollution, and soil erosion. Many people can also increase the consumption and management of waste, both household and industrial waste.

Generally, the increase in Indonesia's population is accompanied by a high level of urbanization. As quoted from World Development Indicators (2023), in 2011, the number of people living in urban areas reached half the total population. By 2022, the population of the urban regions will be 57.93 percent of the total population in Indonesia. The phenomenon of high urbanization is caused by several factors, such as villagers who think that jobs in cities are easier to get and high income, as well as extensive facilities and job opportunities in cities. In Indonesia, the population distribution is still centered on Java, which has 152,787.8 thousand people, making it the most densely populated island.

Economic activity is a country's primary driver of development and socio-economic growth. However, economic growth is often followed by increased consumption of natural resources, which leads to environmental degradation if carried out continuously. Using natural resources, especially fossil fuels used in the economic sector to generate electricity and transportation energy, can result in high carbon emissions. According to Grossman & Krueger (1995), economic growth can affect the environment by changing the industrial structure, increasing production, and expanding economic activity. This is supported by Khan et al. (2018), who state that industrialization activities as a driver of increased economic growth will also cause an increase in carbon dioxide emissions in developing countries.

The value of Gross Domestic Product (GDP) is usually used to measure economic growth. GDP is considered the best indicator of economic performance because, with good economic growth, other variables will be more accessible to develop as well. According to Tsandra et al. (2023), GDP per capita affects carbon dioxide emissions in developed and developing countries, but the effect differs. When referring to the Environmental Kuznets Curve (EKC) hypothesis, developed countries have reached a condition where a decrease in environmental degradation accompanies the rate of economic growth. However, the opposite is true for developing countries. Carbon dioxide emissions are still increasing at the growing GDP per capita stage. This is due to developing countries that easily transfer environmentally friendly technology to minimize environmental damage when carrying out economic activities. In contrast, some developing countries still use traditional technology and often sacrifice environmental sustainability to improve the economy. Diartho & Fardian (2022) also stated that GDP per capita positively affects changes in carbon dioxide emissions, which cause a decrease in environmental quality in Indonesia.

In addition to population and gross domestic product, technology can also affect carbon dioxide emissions. In the study of Ridzuan et al. (2020), Wang et al. (2017), and Zhang & Zhao (2019) state that technology affects carbon dioxide emissions. Based on the argument of Dietz & Rosa (1997), technology is not only the state of machinery or equipment for production owned by the country but also the socio-economic indicators that exist in an economy. Trade openness can be one way to measure the influence of technology. Trade openness also serves as a comparison between countries and evaluates external trends over time. Another way is to look at the sectoral growth of a country. Traditionally, an economy consists of three sectors: agriculture, industry, and services. The economic expansion of these sectors can grow together, although the share in the economy tends to vary, so the impact on environmental quality has been debated in previous studies (Grossman & Krueger, 1995; Panayotou, 1993). Another technological indicator is renewable energy consumption.

Many studies suggest that increasing energy consumption will increase carbon dioxide emissions. Therefore, to avoid this, shifting to renewable energy (including solar, tidal, geothermal, wind power, biomass, and water) is necessary. Using cleaner and environmentally friendly renewable energy will lower carbon dioxide emissions than fossil fuels, considered the leading cause of global warming (Bekun et al., 2023). Renewable energy can be a source of income for the community to open up new employment opportunities in various sectors. Doing so can help expand the economy while reducing environmental pollution so that air quality and public health are improved.

Indonesia's abundant natural resources offer immense potential for the development of renewable energy. However, this potential remains underutilized, necessitating optimization efforts from both the government and society. According to Abbasi et al. (2021), transitioning to renewable energy consumption is crucial for achieving long-term reductions in carbon dioxide (CO_2) emissions. Similarly, Vo et al. (2019) observed that current levels of renewable energy adaptation are insufficient to effectively mitigate CO_2 emissions, highlighting the need for further action.

Extensive research has explored the role of renewable energy in moderating the environmental impact of economic activities. For example, Mentel et al. (2022) found that renewable energy reduces the impact of industrialization on CO_2 emissions in Africa, while Shah et al. (2022) argued that renewable energy helps offset the agricultural sector's contribution to CO_2 emissions and climate change. Despite these findings, existing studies primarily focus on isolated economic sectors or fail to comprehensively examine the interplay of multiple factors influencing emissions. This study introduces several innovative contributions to the literature, first sectoral Impact Analysis. Unlike previous research, this study examines the collective influence of multiple economic sectors (e.g., industrialization, agriculture, and energy) on CO_2 emissions. Second, proposed moderating role of renewable energy: The study explores the moderating effect of renewable energy on the relationship between economic sector growth and CO_2 emissions, addressing a key gap in the existing literature.

Literature Review

The impact of economic sectors is linked to the theory of Environmental Kuznets Curve (EKC) hypothesis, which suggests that the relationship between economic growth and environmental degradation is an inverted U-shape. The agricultural sector, which involves activities including forest clearing, can increase carbon dioxide emissions. This statement aligns with research by Alavijeh et al. (2023) and Kwakwa (2023) that shows that agricultural sector growth increases carbon emissions. However, Raihan & Tuspekova (2022) found a carbon dioxide reduction effect from agriculture in Turkey because tillage reduces fossil fuel use and increases soil carbon sequestration.

Over time, economic development that began to be dominated by industry caused carbon emissions to increase. Ali et al. (2022) stated that the industrial sector was affected by increasing carbon dioxide emissions. This is also expressed by Sikder et al. (2022), who state that industrialization increases carbon dioxide in developing countries. Many studies have reported that the industrial sector's impact could be more environmentally friendly because it wastes energy, thus increasing carbon dioxide emissions. However, Adom et al. (2018) revealed that the efficient industrial sector will produce lower carbon emissions. The manufacturing sector, a derivative of the industrial sector in 2022, contributed 18.34 percent to Indonesia's GDP. This figure is large enough to find the influence of the manufacturing sector on the disclosure of carbon dioxide emissions. Komang & Nyoman (2020) revealed that the manufacturing sector with several indicators did not affect the quality of carbon dioxide emissions.

Higher levels of development are currently dominated by the services sector, which emits less carbon dioxide because it is less energy-intensive. Adebayo et al. (2023) found that structural changes towards the service sector can reduce carbon dioxide in Turkey. In the same year, Ali et al. (2022) found a negative effect of service growth on carbon emissions in Pakistan. However, Martínez & Silveira (2012) found that service sector growth increased Sweden's energy consumption and carbon dioxide emissions. The study emphasized that the growth of the service sector can drive energy use in related energy-intensive sectors. In line with this study, Sohag et al. (2017) also stated that the service sector has the effect of increasing carbon dioxide emissions in middle-income countries.

The hypothesis in this research can be written as:

1) Urban population has a positive influence on carbon dioxide emissions in the short and long term
2) GDP per capita has a positive influence on carbon dioxide emissions in the short and long term

3) Trade openness has a positive influence on carbon dioxide emissions in the short and long term
4) Renewable energy consumption has a negative influence on carbon dioxide emissions in the short and long term
5) The agricultural sector with the moderating role of renewable energy has a negative influence on carbon dioxide emissions in the short and long term
6) The industrial sector with the moderating role of renewable energy has a negative influence on carbon dioxide emissions in the short and long term
7) The manufacturing sector with the moderating role of renewable energy has a negative influence on carbon dioxide emissions in the short and long term
8) The service sector with the moderating role of renewable energy has a negative influence on carbon dioxide emissions in the short and long term

Methods

The ARDL test is one of the cointegration approaches to test whether a long-run equilibrium exists in an economic system. In the ARDL model, a bound test is used to test the long-run relationship; once the relationship is confirmed, the model can estimate the short-run and long-run effects. Compared to other cointegration approaches, the ARDL model can be a valid method when endogenous variables are included in the explanatory variables, and bound testing can be performed with a small sample size (Manzoor et al., 2021).

The model on which this research is based is the STIRPAT model, which aims to allow for random errors in the parameter estimates Dietz & Rosa (1997). This model states that the level of environmental degradation is interpreted as an impact (I), which is a function of population pressure (P), affluence or economic growth (A), and technology (T). The STIRPAT model was used in this research for its ability to analyze the impact of socio-economic and technological factors on environmental changes, such as carbon emissions. It incorporates population, prosperity (affluence), and technology to explain their contributions. The model allows for random errors in parameter estimates, meaning results may contain uncertainties due to unforeseen factors. While these errors add uncertainty, they enhance analytical precision and support the development of more sophisticated statistical techniques and adaptive policies. The mathematical function of this model is expressed as:

$$I = a.P^{\lambda}.A^{\gamma}.T^{\sigma}.v \quad (1)$$

Where a, λ, γ, and σ are the parameters to be estimated, and v is the error (Do Miswa., Kartiasih, 2025). Environmental degradation can be proxied by carbon dioxide emissions because they contribute to global warming and climate change (Kwakwa, 2023). Therefore, carbon dioxide emissions represent impact (I). Population or urban population in the total population will represent population pressure (P) (Helda et al., 2018; Ridzuan et al., 2020). Prosperity (A) is defined by income, GDP per capita (Ojaghlou et al., 2023; Tsandra et al., 2023). Based on the argument of Dietz & Rosa (1997), technology is not only the state of machinery or equipment for production but rather the socio-economic elements that exist in an economy. Like previous research conducted by Ghazali & Ali (2019), Wang et al. (2017), and Zhang & Zhao (2019) state that technology can be in the form of trade openness, renewable energy consumption, and sectoral growth so that these three variables can be included in the model. To make the calculation easier, the equation in the model must be converted into linear form (Shi, 2001), the equation is as follows:

$$lnI_t = a \quad + \lambda lnP_t + \gamma lnA_t + \sigma lnT_t + \varepsilon_t \qquad (2)$$

Where β_0, β_1, β_2, and β_3 are regression parameters while ε indicates errors or residuals. Data transformation with natural logarithm (ln) reduces excessive data instability (Sugiyono, 2013). Transforming equation (2) into an equation that matches the research variables results in the following equation:

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSEC_t + \varepsilon_t \qquad (3)$$

Where t denotes the corresponding time (year), ε denotes the error term, and ln is the symbol for the natural logarithm. To assess the moderating role of renewable energy consumption in the relationship of sectoral growth to carbon dioxide emissions, an interaction between the two (lnREN x lnSEC) is created and added to the model. These interaction between renewable energy consumption and the economic sector is crucial for sustainable growth, as both influence each other. Renewable energy reduces carbon emissions compared to fossil fuels, lowering long-term energy costs and enhancing economic stability. This transition also drives innovation, boosting industrial efficiency, competitiveness, and new market opportunities. Additionally, it supports environmental sustainability and fosters economic development by creating jobs, generating income, and promoting equitable regional growth, especially in underdeveloped areas. The equation can be written as follows:

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSEC_t + \theta(lnREN_t \times lnSEC_t) + \varepsilon_t \qquad (4)$$

Analyzing the moderating role of renewable energy is necessary to determine whether renewable energy variables will strengthen or weaken the relationship between sector growth variables and carbon dioxide emissions variables. This object of this research use 4 main sector, namely agriculture, industry, manufacturing and services The industry sector is a broad category covering economic activities such as mining, manufacturing, construction, electricity, water, and gas. Manufacturing, a sub-sector of industry, specifically involves transforming raw materials into finished or semi-finished products, including food, textiles, chemicals, machinery, and electronics. Services (ISIC division 50-99) include wholesale and retail trade, transportation, financial services, education, healthcare, and real estate. The key difference is that industry encompasses multiple sectors, while manufacturing focuses solely on production. The final models (3) and (4) are used to estimate each sector: agriculture, industry, manufacturing and services.

Since this study is interested in assessing the effect of economic sector growth, namely, the agricultural sector, industrial sector, manufacturing sector and service sector, which are the sectoral components (lnSECT) in equations (3) and (4), the equations are transformed with the agricultural sector (lnAGR), industrial sector (lnIND), manufacturing sector (lnMAN) and service sector (lnSER) to obtain the following equations:

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnAGR_t + \varepsilon_t \qquad (5)$$
$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnIND_t + \varepsilon_t \qquad (6)$$
$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnMAN_t + \varepsilon_t \qquad (7)$$
$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSER_t + \varepsilon_t \qquad (8)$$

The interpretation of the interaction term follows that described in equation 4.

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSEC_t + \theta(lnREN_t \times lnAGR_t) + \varepsilon_t \quad (9)$$

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSEC_t + \theta(lnREN_t \times lnIND_t) + \varepsilon_t \quad (10)$$

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSEC_t + \theta(lnREN_t \times lnMAN_t) + \varepsilon_t \quad (11)$$

$$lnCO2_t = \alpha + \lambda lnUP_t + \gamma lnGDP_t + \sigma lnTO_t + \delta lnREN_t + \beta lnSEC_t + \theta(lnREN_t \times lnSER_t) + \varepsilon_t \quad (12)$$

This study uses quantitative data collected from the World Bank with time series data from 1990 to 2022 in Indonesia. The variables used in this study are as follows:

Table 1. **Variable Units and Sources**

Variable	Description	Units
CO2	Environmental degradation	metric tons per capita
UP	Urban population	Urban population (% of total population)
GDP	Economic growth	GDP per kapita (constant 2015 US$)
TO	Trade openness	Trade (% of GDP)
REN	Renewable energy consumption	Renewable energy consumption (% equivalent primary energy)
SEC	Sectoral growth	
AGR	Agriculture	Agriculture, forestry, and fishing, value added (% of GDP)
IND	Industry	Industry (including construction), value added (% of GDP)
MAN	Manufacturing	Manufacturing, value added (% of GDP)

Findings

Time series data is said to be stationary if its mean, variance, and covariance remain the same (constant) over time. The method often used by econometricians these days to test data stationarity problems is the unit root test. This study used the Dickey-Fuller or Augmented Dickey-Fuller (ADF) unit root test with a probability value of less than the critical value of 5 percent.

Table 2. **Stationarity Testing Results**

Variable	Level		First Difference		Conclusion
	T-stat	Prob	T-stat	Prob	
CO2	-0,9676	0,7526	-4,7874	0,0006	I(1)
UP	-18,9552	0,0001	-1,2007	0,6614	I(0)
GDP	-0,1559	0,9344	-4,2114	0,0025	I(1)
TO	-2,1550	0,2258	-7,4670	0,0000	I(1)
REN	-0,3131	0,9121	-7,5479	0,0000	I(1)
AGR	-2,1757	0,2185	-5,7176	0,0000	I(1)
IND	-1,9478	0,3073	-5,6180	0,0001	I(1)
MAN	-1,2418	0,6437	-6,1031	0,0000	I(1)
SER	-1,0466	0,2666	-5,7707	0,0000	I(1)

Source: Processed Data Eviews (2024)

Based on Table 2. testing with Augmented Dickey-Fuller (ADF) at the level obtained the result that the urban population (UP) variable does not contain unit roots or stationary at the first difference level. While the variables of carbon dioxide emissions (CO2), GDP per capita (GDP), trade openness (TO), renewable energy consumption (REN), agricultural sector (AGR), industrial sector (IND), manufacturing sector (MAN), and service sector (SER) contain unit roots, so it is necessary to test at the first difference level. After testing stationarity at the first difference level, the results show that the variables of carbon dioxide emissions, GDP per capita, trade openness, renewable energy consumption, agricultural sector, industrial sector, manufacturing sector, and service sector are stationary, as seen from the probability value which is less than 5 percent alpha.

Table 3. **Lag Optimum**

Agriculture sector model						
Lag	LogL	LR	FPE	AIC	SC	HQ
0	159.017	NA	2.08e-12	-9.872	-9.5945	-9.781
1	391.755	360.368	6.70e-18	-22.564	-20.622*	-21.931
2	442.512	58.944*	3.43e-18*	-23.516*	-19.908	-22.340*
Industry sector model						
Lag	LogL	LR	FPE	AIC	SC	HQ
0	169.773	NA	1.04e-12	-10.566	-10.288	-10.475
1	389.470	340.177	7.76e-18	-22.417	-20.474	-21.784
2	454.358	75.353*	1.60e-18*	-24.281*	-20.673*	-23.105*
Manufacturing sector model						
Lag	LogL	LR	FPE	AIC	SC	HQ
0	148.633	NA	4.06e-12	-9.202	-8.924	-9.111
1	375.569	351.384	1.90e-17	-21.520	-19.577	-20.887
2	445.684	81.424*	2.80e-18*	-23.721*	-20.113*	-22.545*
Service sector model						
Lag	LogL	LR	FPE	AIC	SC	HQ
0	169.901	NA	1.03e-12	-10.574	-10.296	-10.483
1	401.014	357.852	3.69e-18	-23.162	-21.219*	-22.528
2	458.304	66.531*	1.24e-18*	-24.535*	-20.927	-23.359*

Source: Processed Data Eviews (2024)

The optimum lag test is carried out to estimate the ARDL model's length of inaction or show the effect of the time interval on the study. This study selects the optimum lag length using the Akaike Information Criteria (AIC) value approach for each of the smallest lags. Based on Table 3, the minimum AIC value is located at lag 2 when testing the optimum lag of the entire model.

Table 4. **Bound Test Cointegration Test Results**

Agriculture sector model				
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	7.667197	10%	2.08	3
k	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15
Industry sector model				
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	5.256871	10%	2.08	3
k	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15

Manufacturing sector model				
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	8.896175	10%	2.08	3
k	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15
Service sector model				
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	6.340947	10%	2.08	3
k	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15

Source: Processed Data Eviews (2024)

Time series data only shows a trend that causes the data to be non-stationary. Cointegration testing is necessary to see the long-term equilibrium relationship because the time series data shows an equilibrium relationship in the short term. The cointegration bound test is used when research variables are stationary at different levels. If the calculated F value is smaller than the lower bound value I(0), it means that there is no cointegration, whereas if the calculated F is greater than the upper bound then there is cointegration. So from the table 4, can be conclude that urban population variables, GDP per capita, trade openness, renewable energy consumption, and sectoral growth with the proxy of the agricultural sector, industrial sector, manufacturing sector, and service sector on carbon dioxide emissions in Indonesia has a cointegration relationship.

Table 5. **Diagnostic Test Results (Probability Value)**

Variable	**Agriculture Sector**	**Industry Sector**	**Manufacturing Sector**	**Services Sector**
Normality Test (prob. Jarque-Bera)	0.599146	0.376511	0.519605	0.868533
Heteroscedasticity Test (Prob. Chi-Square)	0.5617	0.8603	0.3117	0.5849
Linearity Test (Prob. F-Statistic Ramsey Reset Test)	0.5679	0.4101	0.9677	0.5430

Source: Processed Data Eviews (2024)

Table 6. **Estimation Results of Long-Term ARDL Model**

Variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
LNPU	1.297***	1.437***	2.641***	2.382***	-0.676	0.378	3.841***	3.345***
LNPDB	0.233	0.111	-0.334	-0.243	1.345***	0.861**	-0.557	-0.544
LNTO	0.117	0.044	-0.074	-0.115	0.741***	0.467**	-0.059	-0.162
LNREN	0.055	3.302***	0.121**	-3.086	0.182**	-4.346*	0.099**	6.512
LNAGR	0.053	1.770***						
LNRENLNAGR		-1.257***						
LNIND			-0.082	-0.926				
LNRENLNIND				0.877				
LNMAN					0.357*	-1.562*		
LNRENLNMAN						1.499*		
LNSER							0.249	2.452
LNRENLNSER								-1.702
C	-7.028***	-10.773***	-6.956***	-3.408	-11.625***	-5.163**	-11.433***	-17.313**

Notes: *** significant at α (1%); ** significant at α (5%); * significant at α (10%); LN, natural logarithm of all variables; PU, urban population; GDP, gross domestic product per capita; TO, trade openness; REN, renewable energy consumption; AGR, agricultural sector; IND, industrial sector; MAN, manufacturing sector; SER, service sector; RENAGR, interaction of renewable energy consumption with agriculture sector; RENIND, interaction of renewable energy consumption with industry sector; RENMAN, interaction of renewable energy consumption with manufacturing sector; RENSER, interaction of renewable energy consumption with service sector.

Table 7. **Estimation Results of Short-Term ARDL Model**

Variable	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
D(LNPU)			4.940	4.540	-14.597***		34.403***	23.710***
D(LNPU(-1))			9.859**	9.392**	6.916			
D(LNPDB)			0.277	0.295			0.218	-0.122
D(LNPDB(-1))			0.774***	0.471**			0.970***	0.638***
D(LNTO)	0.130***	0.050	0.155**		0.256***	0.224***	0.131**	0.150**
D(LNTO(-1))	0.202***	0.194***	0.367***	0.213***		0.175***	0.357***	0.317***
D(LNREN)	-0.140***	1.138*	-0.131***	2.819*	-0.078**	2.924***	-0.106***	-2.887
D(LNREN(-1))	-0.150***		-0.135***		0.125***		-0.155***	-0.154***
D(LNAGR)	-0.155	0.460						
D(LNRENLNAGR)		-0.482**						
D(LNRENLNAGR(-1))		-0.040***						
D(LNIND)			-0.730***	0.527				
D(LNRENLNIND)				-0.785*				
D(LNRENLNIND(-1))				-0.044***				
D(LNMAN)					-0.316***	-0.060		
D(LNMAN(-1))					-0.328***	0.938***		
D(LNRENLNMAN)						-0.070		
D(LNRENLNMAN(-1))						-1.003***		
D(LNSER)							0.898***	-0.399
D(LNSER(-1))							0.343**	
D(LNRENLNSER)								0.741
CointEq(-1)*	-0.925***	-1.055***	-0.845***	-0.898***	-0.784***	-0.832***	-0.937***	-0.879***

Notes: *** significant at α (1%); ** significant at α (5%); * significant at α (10%); LN, natural logarithm of all variables; PU, urban population; GDP, gross domestic product per capita; TO, trade openness; REN, renewable energy consumption; AGR, agricultural sector; IND, industrial sector; MAN, manufacturing sector; SER, service sector; RENAGR, interaction of renewable energy consumption with agriculture sector; RENIND, interaction of renewable energy consumption with industry sector; RENMAN, interaction of renewable energy consumption with manufacturing sector; RENSER, interaction of renewable energy consumption with service sector.

Table 5 shows the result of diagnostic testing of all models. The normality test shows that the probability value of the Jarque Bera Test is greater than the critical value of 0.05, meaning that the residuals are distributed normally and proving that the data in the study does not have normality problems. The heteroscedasticity test shows the prob value. Chi-Square from the research results shows a value greater than the critical value of 0.05, meaning there is no heteroscedasticity problem. This proves that the variance regression model in this study is homoscedastic. Meanwhile, the linearity test shows all models' Ramsey Reset Test F-statistic results. The F-statistic value of the research results is greater than the critical value of 0.05, meaning that the model used is appropriately specified or linear.

Based on Tables 6 and 7, renewable energy consumption is seen in the agricultural and industrial sectors to have a negative relationship with carbon dioxide emissions. An increase in renewable energy consumption is associated with a reduction in carbon dioxide. This finding aligns with research showing that renewable energy is environmentally friendly and more efficient than fossil fuels (Gyamfi et al., 2023). However, in the service sector, renewable energy consumption has little effect. Meanwhile, the manufacturing sector shows that renewable energy consumption positively correlates with carbon dioxide emissions. This is because renewable energy can trigger higher carbon emissions when it drives economic growth and leads to increased demand for energy-intensive gadgets (Yang et al., 2022).

The expansion of economic activity on carbon dioxide emissions in Indonesia can be observed from these four sectors. From the study results, the agricultural sector does not have a significant relationship with carbon dioxide emissions in the long term or short term. Indonesia's agricultural sector, mainly the small to medium-scale ones, relies more on human labour and simple farming tools. Immense fossil fuel use contributes to CO_2 emissions and is generally more dominant in the industrial and transportation sectors. In contrast, the agricultural sector is less involved in burning fossil fuels in daily operations.

The results of this study align with research conducted by Xu et al. (2022) that the agricultural sector has a negative effect on carbon dioxide emissions, thereby reducing environmental degradation. Sustainable practices in the agricultural sector that reduce carbon dioxide emissions can also act as carbon sinks, such as using organic fertilizers and waste management that can improve soil fertility. Such practices occur due to the moderation of renewable energy, which helps reduce carbon dioxide emissions and is more efficient. The results of this study have concurrent findings from Kwakwa (2020) and Shah et al. (2022).

Industrialization in the long term does not affect carbon dioxide emissions in Indonesia; in the short term, it has a negative and significant effect. One of the factors that cause this negative effect is the minimal use of fossil fuels in industrial activities. In addition, the moderating role of renewable energy can be an environmentally friendly alternative energy in the application of the industrial sector. The results of the study align with the findings by Mentel et al. (2022), who found that using renewable energy helps reduce the impact of industrialization on carbon emissions in Africa. Claire & Widyawati (2023) also stated that renewable energy can reduce the environmental impact of industrialization on carbon dioxide emissions in several countries. Reliance on clean energy sources for industrial activities will continue to be associated with higher carbon dioxide emissions. However, the shift to renewable energy, which is cleaner and more efficient, makes the industrial process less polluting, leading to low carbon dioxide emissions.

In the development of industrialization, the manufacturing sector emerged as one of the contributors to the gross domestic product in Indonesia. The manufacturing sector influences carbon dioxide emissions in the long term and short term. This aligns with research conducted by Karedla et al. (2021), which stated that the manufacturing industry significantly influences local carbon dioxide emissions. Still, there is no impact on the surrounding area. The findings of Avenyo & Tregenna (2022) state that the manufacturing sector increases carbon dioxide emissions because the technology used is still low. Low-tech manufacturing activities include industries such as wood, pulp, and paper.

In the country's stage of economic development, the service sector has, in recent years, dominated other sectors at higher levels of development. In the short term, Indonesia's service sector is observed to increase carbon dioxide emissions. The results of this study align with research conducted by Butnar & Llop (2011) and Samargandi (2017), which found that the service sector can cause increased carbon dioxide emissions. Energy is needed in the service sector for lighting and cooling office space and many equipment that use energy. Even the moderation of renewable energy consumption does not help reduce carbon dioxide emissions in the service sector. This is because the service sector in Indonesia is not environmentally friendly and inefficient in reducing carbon dioxide emissions. Indonesia's service sectors that are not environmentally friendly and inefficient in reducing carbon dioxide emissions include transportation, energy, hospitality and waste management. Transportation services, such as public transport and private vehicles, still rely on fossil fuels that produce CO_2 emissions. The energy sector also relies heavily on fossil fuel power plants that contribute to carbon emissions. In addition, the hospitality and tourism sector requires large amounts of energy and often does not implement environmentally friendly practices. Inefficient waste management also exacerbates the problem of waste incineration producing emissions. The study's results align with Yang et al. (2022).

The results in Tables 6 and 7 also show another finding: in the long run, except for the manufacturing sector, the urban population has a positive relationship with carbon dioxide emissions. According to Adom et al. (2018), environmental pressures due to urbanization occur through various actions, including clearing forest resources for office and residential buildings, heavy vehicle traffic, and slum conditions. This is supported by research by Widyawati et al. (2021) that shows that the urban population has a significant positive effect on carbon dioxide emissions. The daily activities of city residents contribute to high carbon dioxide emissions. Various activities can increase the use of fossil fuels, which will ultimately cause environmental pollution. This is also caused by the number of urban populations with low awareness of daily activities that will affect the environment.

The effect of GDP per capita does not appear in the short-run empirical results. Still, the manufacturing sector indicates that GDP per capita causes more carbon dioxide emissions in the long run. The results of this study align with research conducted by Nguyen (2019) and Ojaghlou et al. (2023) that high GDP per capita will increase economies of scale and negatively impact environmental quality. This condition occurs because the environment cannot keep up with the acceleration of economic growth, making the environment a victim. After all, it is only considered as an input factor. The findings also show that increasing per capita income is still a development priority, but environmental quality is a sidelined indicator.

Trade openness positively affects the manufacturing sector's carbon dioxide emissions in the long run and all sectors of the economy in the short term. It can also encourage production growth to meet broader market demand. Increased production often requires a lot of energy and resources, which can be a factor in reducing environmental quality. This study's results align with Dou et al. (2021) and Vural (2020) findings.

Conclusion

Indonesia's rapid economic growth in recent years has been an impressive phenomenon. However, the effect of increased carbon dioxide emissions from 1990 to 2022 is a matter of concern. Expanding economic activities in the agriculture, industry, manufacturing, and services sectors can be given more attention so as not to become a factor in environmental damage. Thus, it is necessary to adopt renewable energy to reduce the impact of carbon dioxide emissions. However, the development of renewable energy consumption in Indonesia still needs to overcome the increase in carbon emissions in the manufacturing and services sectors. The STIRPAT model also shows that population, affluence, and technology indicators have a positive relationship with carbon dioxide emissions in Indonesia.

This study must consider that the government must educate urban residents to consume products that can reduce environmental damage and provide intensive support for producers to produce environmentally friendly products. These can be renewable energy-based products like solar panels or energy-efficient lamps. These products can reduce dependence on fossil energy and reduce negative impacts on the environment. Other products include organic food products and eco-friendly packaging connected to reducing carbon dioxide emissions, although not directly. Organic food is produced without pesticides or synthetic chemicals that require fossil energy and often involves more sustainable farming practices, which can reduce CO_2 emissions. Environmentally friendly packaging, such as those made from recycled or biodegradable materials, reduces the use of single-use plastics that require fossil energy and avoids burning plastics that produce CO_2. Both of these products contribute to reducing the overall carbon footprint through more sustainable means. The government must also increase the development of renewable energy potential in Indonesia to reduce carbon dioxide emissions. This can be done by attracting foreign direct investment, specifically in the renewable energy sector.

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