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THE IMPACT OF INDUSTRIALIZATION AND SELF-RENEWING ENERGY UTILIZATION ON CARBON DISCHARGES IN THE COUNTRY ECONOMICS

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Abstract. Industrialization has been pivotal in driving economic development. The research problem is the negative impact of industrialization to global warming and climate change. The relevance – enabling the use of renewable energy and green solutions to decrease CO_2 emissions. This research aims to evaluate the impact of short and long-term of industrialization, consumption of renewable energy, trade openness and economic growth on carbon emissions per capita in Indonesia. This research analyses [2000–2023] data, applying econometric ARDL approach and diagnostic tools. The Breusch-Godfrey Serial Correlation (BGSC) results revealed no consistent correlations, when Breusch-Pagan-Godfrey (BPG) test heteroscedasticity was confirmed. Ramsey RESET test (RRT) showed that the model is perfectly specified and significant; CUSUMSQ and CUSUM tools proved the stability of the model, when the VIF multicollinearity results indicated that no multicollinearity exists between the variables. Research findings show: trade openness and the consumption of renewable energy demonstrate a favourable effect for carbon output per capita in Indonesia as outcomes of economic progress, while industrialization has an adverse relationship with emissions of carbon per capita. The research originality – complex evaluation of the relationship between mentioned variables interplay. This publication provides recommendations for policymakers to improve the quality of environment.

Keywords: industrialization, economic growth, renewable energy, carbon discharges.

JEL Classification: O14, O40, Q40, Q42, F62, F64.

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1. Introduction

In recent years, industrialization occupies an increasingly relevant place in the development of countries' economies, when consumption of renewable energy becomes a significant factor which is contributing to enhanced environmental sustainability. It is swiftly becoming rising pivotal challenge between others for development of industry (Malik et al., 2024; Adebayo & Ullah, 2024). Besides, to reach the Sustainable Development Goals, attaining environmental sustainability is crucial (Dogan et al., 2024). For achieving environmental sustainability, developed high-income countries are applying many various pro-environmental initiatives aimed at reducing emissions in every country's sector relating with environment in a straightforward or roundabout way (Jahanger et al., 2024).

In the 21st century, there are many challenges in the world. One of the main challenges is global warming and climate disruption, mainly caused by growing CO_2 outputs (Acaroğlu

et al., 2023; Hardi et al., 2023; Li et al., 2023). CO_2 discharges 74.4% of the total outputs becoming the major contribution to atmospheric warming and its environmental impacts (Islam et al., 2022). Based on Global Atmospheric Research database, total CO_2 discharges in Indonesia grew from 611.82 mil. tons in 2021 till 692.24 in 2022. Indonesia has the highest total CO_2 discharges as the country within Association of Southeast Asian Nations (Crippa et al., 2023). Although every country has committed to reducing carbon emissions to prevent such devastation (Erdogan et al., 2023).

The rapid growth of industrialization transformed agrarian economies into industrial economies, significantly enhancing living standards and welfare. However, urbanized and industrialized economies have simultaneously presented substantial challenges to environmental sustainability (Ahmed et al., 2022). Indonesia's industrial growth has seen a significant rise over the past few years. Based on the World development indicators, Indonesia's industry economic contribution (GDP in %) increased from 39.8% in 2021 till 42.4% in 2022 (World Bank Group, n.d.). As industrialization progresses, environmental concerns increase (Opoku & Aluko, 2021). Likewise, the industrial segment is the main energy user and the highest emitter of CO_2 among all final sectors (Zhang et al., 2020). The leading cause of CO_2 discharges in Indonesia – production of electric power and heat, which accounts for 43.2% of Indonesia's overall discharges, while the manufacturing sector contributes 23.5% of the total carbon discharges (International Energy Agency [IEA], 2024).

Self-renewing power consumption is essential for lowering carbon discharges and promoting sustainable development (Işık et al., 2024). When it comes to mitigating climate change, investing in renewable energy is crucial (Adebayo, 2024). The International Energy Agency projected that the consumption of electric power of Indonesia would rise till 80% in 2030, while the nation's energy demand would quadruple. Investments in renewable energy must increase rapidly if Indonesia is to meet its targets. Furthermore, the use of renewable resources will enhance Indonesia's self-sufficiency, ultimately resulting in a 10% reduction in the need for fossil fuels. Indonesia ranks among the top five nations in the Asia-Pacific region in terms of renewable energy capacity, with the majority coming from geothermal and hydroelectric facilities, which account for 5% and 8%, respectively (Tachev, 2024). Recently, global renewable energy consumption increased from 14.12% to 14.56% between 2022 and 2023. Similarly, in Indonesia, renewable energy consumption rose from 9.90% to 10.45% during the same period.

In the 21st century, industrial expansion ushered in a new era of economic development among countries. However, it also precipitated several challenges, including climate change and global warming (Mitić et al., 2023). To attain sustainable growth, there is a need to reconcile the conflict evaluating interaction of economic advancement and carbon discharges (Wang et al., 2022a). Likewise, the primary driver of CO_2 emissions is income per capita (Parker & Bhatti, 2020). In recent years, Indonesia's economy has significant growth, with rate of increase in GDP per person increasing from 2.99% in 2021 till 4.62% in 2022 (World Bank Group, n.d.). However, during the same period, carbon discharges per person in Indonesia grew from 2.2 till 2.6 tons (2021–2022). See Figure 1 (Our World in Data [OWID], 2022).

The originality of the research – the complex estimation of the relationship between these variables: industrialization, consumption of self-renewing power, trade openness and economic growth as well as carbon discharges per capita in the country of Indonesia. This research

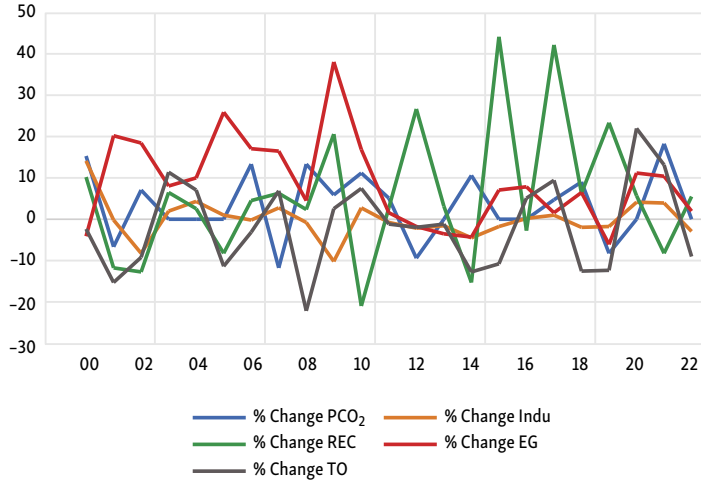

Figure 1. Variations of carbon discharges per person, industrialization, consumption of self-renewing energy, trade openness and economic growth in Indonesia (2000–2023) (prepared by authors, 2024)

addresses to fulfil the lack in existing literature regarding the complex relationship within industrialization, renewable power consumption, and carbon discharges variables. It extends this study and delivers useful perspectives for the future investigations into the underlying factors driving this relationship. In the modern era, industrialization has been a significant contributor to economic development because industrial development depends on energy consumption, resulting in greater energy use and accelerated economic development. Consequently, carbon emissions also increase. Addressing the environmental impact of industrialization is a critical global challenge, making scientific research in this area of utmost importance. This research work engages to the global conversation relating sustainable economic growth in analyzing the case of Indonesia, a country experiencing rapid industrialization and facing significant environmental challenges. Indonesia has been chosen for this research because it ranks among one of the world's quickest-growing economic growth performers and one of carbon-emitting top countries globally. Indonesia also is among top-emitting countries within an international group of countries that includes 19 of the world's largest economies and the European Union (Group of 20 -G-20). Indonesia is a key player in global environmental sustainability efforts. Past few decades showed that Indonesia's industrial sector has expanded due to economic growth, raising concerns about its environmental impact. This research covers the period from 2000 to 2023 (latest available data), during which industrialization and energy consumption have been closely linked to economic activities. Both have increased, resulting in increased development as well as higher carbon emissions. This study is unique because: a) it evaluates the influence of industrialization, consumption of self-renewing power, economic growth and trade openness, on carbon discharges per capita of Indonesia; b) industrialization is used as a more accurate proxy for economic progress. The practical implications of current study support environmental economics. Research findings provide a roadmap for stakeholders to create policies for environmental sustainability in relation to economic development. Recommendations based on this research will not only benefit Indonesia but also the

international groups of countries: ASEAN, G-20), and the Organization of Islamic Cooperation (OIC), as Indonesia is a key member of these organizations, and its environmental policies have regional and global implications.

The estimated objectives of this study are:

1. To carry out the impact analysis of industrialization, trade openness, renewable energy, and economic growth on CO_2 emissions in the country of Indonesia during the period of 2000–2023.
2. To compile the model and evaluate the long-run and short-run relationships between industrialization, renewable energy, trade openness, and economic growth's variables on CO_2 emissions in the country (Indonesia) economics.
3. To evaluate positive and/or negative impact of industrialization and renewable energy consumption on environmental sustainability and economic growth in Indonesia.

2. Literature review

The present study reveals a relationship between industrialization and self-renewing energy on CO_2 discharges, revealing the mutual influence of economic growth.

2.1. Research methods

The aim of the research is to evaluate whether industrialization and consumption of renewable power, trade openness, and economic growth have a negative and/or positive short-run and long-run impact for environmental sustainability, CO_2 discharges per capita, and growth of the economy in Indonesia. To reach desired outcomes, the research uses the tool: Autoregressive Distributed Lag (ARDL) econometric approach, fits well to evaluate short-run and long-run interrelationships between variables. Industrialization, trade openness, self-renewing power, and economic progress variables are required to be stationary when applying the ARDL method. Therefore, statistical methods for data analysis need to be applied. The tool of Augmented Dickey-Fuller (ADF) test is applied, which examines whether the indicators (CO_2 emissions, industrialization, consumption of self-renewing power, trade openness, and economic progress) are stationary, meaning they do not change over time. Once stationarity of the indicators is verified, the ARDL bounds test is used to assess whether a cointegration connection exists between the variables, suggesting a stable long-term interconnection. In the case when indicators demonstrate cointegration, the ARDL approach can then be performed to analyze short-run and long-run dynamics. In addition to these core tests, several tests for diagnostic analysis are employed to improve the accuracy and trustworthiness of the research results. These can be categorized into 4 (four) main stages. Firstly, Stationarity and Cointegration Tests are used: the ADF tool is applied for checking the indicators' stationarity, while the tool of ARDL bounds test examines cointegration between variables, after which the ARDL model is applicable. Secondly, the Model Specification Tests are used: the tool of Breusch-Godfrey test checks for successive correlation in the model to check if the it is properly defined; other statistical tool – the BPG, in regression model detects heteroscedasticity, confirming that the model's error variance is consistent; next – the Regression Equation

Specification Error Test (Ramsey RESET) – assures that the model reliably demonstrates the interaction among chosen variables and is free from specification errors. In the third stage Model Stability Tests are used: Cumulative Sum of Squares (CUSUMSQ) and the Cumulative Sum (CUSUM), which are employed to assess the stability of the model in the long run, as well as detect any structural breaks that might affect the results. In the 4th stage Multicollinearity Variance Inflation Factor (VIF) Test is used is applied to detect strong correlation between variables, ensuring that the independent indicators are not highly correlated with one another, which could distort the regression results. By integrating these econometric techniques, this study not only ensures methodological accuracy but also enhances the reliability of results.

This research is organized into three main parts. The research starts with an introduction. The first part explains the literature review and how previous studies interlink the research variables and carbon emissions. The second part explains the research methodology and how the research objectives are achieved. The third part is presenting empirical research results, when the paper is finalized with conclusions and recommendations based on the research outcomes.

2.2. CO_2 emissions and industrialization

CO_2 discharges are a major driver of degradation of environment influenced by human activities. Also, CO_2 emissions impact on the environment and are central in sustainability framework (Shaikh et al., 2024). Industrial development has resulted in pollution by ignoring issues of the environment and employing not sustainable industrial systems. Industrial development is the primary driver of increasing discharges, declining the environmental quality. There is a need for in-depth study causing of the socioeconomic factors causing CO_2 discharges (Kakar et al., 2024). The interconnection among industrialization and carbon discharges variables has been thoroughly researched, yet the findings remain inconsistent (Yu et al., 2024). A number of scholarly research papers imply the fact proving when industrialization and CO_2 discharges demonstrate a positive interaction (correlation) (Amoah et al., 2024; Chandra Voumik & Ridwan, 2023; Raihan et al., 2023; Touati & Ben-Salha, 2024; Thi Quy et al., 2024), especially when countries are rapidly developing after financial development, industrialization (Thi Quy et al., 2024). For instance, trade openness and usage of electric power contribute to carbon discharges (Ali et al., 2025). Research conducted in countries of GCC (Gulf Cooperation Council) (in the period of 2000–2021 utilized the CS-ARDL approach, revealing that industrialization adversely affects environmental quality (Touati & Ben-Salha, 2024). A similar research conducted in 28 Sub Saharan African (SSA) countries shows that industrialization positively impacts carbon emissions (Amoah et al., 2024). But industrialization poses long-term environmental harm in Argentina (Chandra Voumik & Ridwan, 2023). Moreover, another research outcome indicates that a 1% rise in industrialization will increase carbon emissions by 0.06% in Thailand (Raihan et al., 2023). Thus, countries willing to progress and improve economy, therefore they are moving to higher energy consumption reaching to raise their industrial profile (Thi Quy et. al., 2024).

Other scholarly studies present contrasting results, indicating a negative relationship between industrialization and CO_2 emissions (Cahyo et al., 2023; Lin et al., 2015). According to another scholarly research, industrialization showed a substantial adverse effect on

Indonesia's CO_2 emissions from 1990 to 2021 (Cahyo et al., 2023). Similarly, research outcomes indicate the influence of industrialization as enhanced value had a notable negative correlation with carbon discharges from 1980 to 2011 in Nigeria (Lin et al., 2015).

Industrial development process enhances economic development through promoting innovation, manufacturing vital products and maximizing resource efficiency. However, the demand for energy use increases together with growing industry. Conversely, CO_2 after electric power usage worsens the surrounding environment and has an indirect impact on economic progress (Kakar et. al., 2024). There is a need of lasting strategies to address health issues linked to carbon dioxide discharges and city growth particularly in SAARC (South Asian Association for Regional Cooperation) economies. Health issues are related to mortality rates. And the research proves that industrialization impacts CO_2 increase and benefit infant mortality in long as well in short-run periods (Guo et.al., 2025). There is a need to boost renewable efficiency of energy and diminish CO_2 discharges and encourage carbon-friendly economic initiatives in countries (Kakar et al., 2024). Overseeing urban growth and decreasing carbon output becoming key approaches to deal with environmental crisis and promote responsible progress (Mehmood et al., 2024).

2.3. CO_2 emissions and renewable energy consumption

Over the last years, the global significance of self-renewing power has grown (Nan et al., 2022). Likewise, self-renewing power is an alternative means carbon emissions reducing tool (Wang et al., 2022b). But its outcomes have been particularly inconsistent throughout various countries and territories (Altın, 2024; Khan et al., 2022; Muhammad et al., 2022). Studies by various scientists reveal that in 27 OECD (Organization's for Economic Cooperation and Development) countries, there is a negative correlation among renewable energy and CO_2 discharges as variables (Işık et al., 2024). Similarly, research in Sweden spanning from 1990 to 2020 demonstrates an inverse association among self-renewing power usage and CO_2 discharges in both: the long term and short term (Adebayo & Ullah, 2024). Additionally, research in the ASEAN regions indicates that the usage of self-renewing power lowers CO_2 discharges and enhances ecological condition (Tran et al., 2024).

Some research studies reveal that self-renewing power is damaging to the surrounding environment, exhibiting a positive relationship among renewable energy and CO_2 discharges (Altın, 2024; Menyah & Wolde-Rufael, 2010; Apergis et al., 2010). The latest research in Group of 7 countries (Canada, USA, France, Japan, Germany, UK and Italy) in the period of (1971–2023), indicates that utilization of self-renewing power demonstrates a positive correlation with CO_2 discharges, contrary to general expectations (Altın, 2024). Another research results indicate that renewable energy consumption increases CO_2 emissions in the USA (Menyah & Wolde-Rufael, 2010). Similarly, research across 19 developed and developing countries from 1984 to 2007 demonstrates that depletion of renewable power does not aid in decreasing CO_2 discharges (Apergis et al., 2010).

Renewable energy sources are extremely important for environmental crisis, significantly contributing to reducing CO_2 emissions, and for promoting eco-friendly economic progress. Utilization of self-renewing power expects to reduce CO_2 discharges and help mitigate atmospheric changes as well as climate disruption problems in the globe. From the other

side, self-renewing power is an important variable contributing also to sustainable economic growth by reducing emissions of carbon dioxide. Research papers prove the information: GDP growth expands as well as coal, crude oil utilization, CO_2 emissions. Other authors found the relation between increase in population and welfare that influencing (increasing) CO_2 emissions. Researchers also prove that CO_2 emissions positively impact energy production. Nonetheless, a downward trend was found in discharges as a result of population growth, welfare improvement, also application of innovative technologies. Therefore, it is suggested to use self-renewing power sources rather than non-renewable energy sources for ensuring economic growth together with environmental quality (Shabani, 2024; Zuhal & Göcen, 2024; Kuziboev et al., 2024; Çobanoğulları, 2024).

Summarizing this subsection, renewable energy consumption is one of the significant contributors in increasing sustainable growth of economy and eco-friendly conditions. It may be noted: utilization of self-renewing power significantly influences carbon dioxide discharges. Authors highlight the high demand of self-renewing power in minimizing long-term and short-term greenhouse gases (Zuhal & Göcen, 2024; Chui et al., 2024). This research results will offer policymakers important perspectives relating development/improvement of productive energy approaches in countries aiming for mitigating emissions and fostering green and effective responsible consumption culture.

2.4. CO_2 emissions and economic growth

From a theoretical perspective, when a country's economic growth is increasing, there are greater opportunities for numerous economic and industrial activities, thus enhancing the likelihood of CO_2 discharges consumptions (Mahmood et al., 2022). Many research studies indicate economic growth and carbon emissions have positive connections (Ahmed et al., 2021; Khanal et al., 2022). For instance, research conducted in Australia from 1976 to 2019 using the ARDL method found that there is a positive and significant relation between economic growth and carbon emissions (Khanal et al., 2022). In the Liu et al. (2022) research of the USA case in the period of 1970 –2020 the Fourier ARDL Approach was employed. The results in both the long-run and short-run periods show that economic growth escalates with carbon emissions. However, from 1974 to 2017, there was evidence that Japan's economic expansion was influenced of enhanced CO_2 discharges (Ahmed et al., 2021).

Economic growth raised environmental crises to a high level, when carbon discharges also increased, influencing the environment. Due to constantly increasing carbon discharges, climatic greenhouse gases compositions significantly rising. Researchers found that CO_2 emissions have a considerable beneficial effect on growing the economy over the short timeframe but have an adverse effect in the long term. Based on Kyoto Protocol, signed by over 100 countries in 1997, they agree on CO_2 reducing target in the biggest developed nations. Moreover, it was prioritizing research directions oriented to reduce CO_2 emissions and balance economic development worldwide. The research results show that GDP (economic factor) influences (encourages) energy consumption which affects CO_2 emission (Pradhan et al., 2024; Mehmood et al., 2024). Innovations are helping countries to move forward and create a stronger economy. Latest research papers prove the positive influence of innovations and CO_2 emission (Saleem, 2025).

The present study aims to support academic literature on environmental economics topics. (i) This research investigates the short and long -run correlation among industrialization, trade openness, consumption of self-renewing power, economic growth on CO_2 discharges in Indonesia. (ii) Per capita amount of emissions proxies are used to measure CO_2 levels. (iii) Before applying the ARDL method, two conditions must be met: the variables must be stationary, and a cointegration relationship must exist. The ADF tool checks variables stationarity, when the ARDL Bounds tool confirms if a cointegration relationship between variables exists. If both conditions hold, the ARDL approach can be utilized to analyze short and long-run. Various diagnostic examinations are carried out to guarantee the precision of the research results. Model Specification tools for calculation approach comprise the Breusch-Godfrey tool for autocorrelation, the tool of RRT – to ensure correct approach outline, and the tool of BPG - to check heteroscedasticity. Model robustness tests involve the CUSUM test to assess stability, and the CUSUMSQ test to identify any structural breaks. Finally, the Multicollinearity Test uses the VIF test to detect multivariate collinearity between the independent indictors. The central concept of present study is to explore the correlation among industrialization, consumption of self-renewing power, economic growth and trade openness on CO_2 discharges in Indonesia. This study is valuable for decision-makers aiming to harmonize economic progress with CO_2 decrease strategies.

2.5. Research methodology

This research examines the short and long-run influence among industrialization, self-renewing power, trade openness, economic progress, and carbon discharges in Indonesia. The main variable of this research is CO_2 per capita discharges (Li et al., 2021) as the dependent variable. However, other variables such as industrialization (Gao et al., 2024), renewable energy consumption (Kwilinski et al., 2024), progress of economy (Jia et al., 2024) are used as independent variables, when trade openness (Chhabra et al., 2023) is used as a benchmark indicator. The study applies a quantitative technique. Data is gathered from the World Bank Group (n.d.) and OWID (2022), spanning twenty-four years of data in the period of 2000–2023. To fulfill the research aim, current study uses the ARDL technique. The ARDL technique has benefits, such as being applicable with a small number of data observations. The key benefit of the ARDL approach – it can be utilized to examine both the short and long-run interrelationships between the main variables and other independent indicators. Furthermore, before applying for ARDL, some conditions must be met. If these conditions exist, the ARDL method is applicable. For instance, ADF unit root tools are necessary to verify if the time series exhibits stationarity resulting from a unit root. Similarly, to investigate cointegrated relationship among indicators (carbon dioxide, industrialization, trade openness, renewable energy, and economic growth), the ARDL Bounds tool is employed. If the test statistics are greater than the minimum and maximum ranges, it means the variables are cointegrated. If latter circumstances are valid, then the ARDL technique is suitable under investigation in this research.

To secure more reliable findings, current study also utilizes different diagnostic tools. For example, the BGSC tool, which is intended to check if there is any pattern or dependence in

the residuals (errors) of a regression approach. If the test results show no serial correlation, it indicates that the approach is appropriately formulated and the results are reliable, and vice versa. Similarly, the BPG tool is checking the heteroscedasticity, which occurs when the variance of errors is not constant. If BPG tool confirms no heteroscedasticity, it means – approaches standard errors are reliable, ensuring accurate statistical inferences and valid results. Furthermore, the Ramsey RESET test is checking if a regression model is correctly specified, meaning it accurately represents the relationship between variables. If Ramsey RESET test shows the perfectly specified model, it suggests there are no misspecifications or omitted variables, ensuring reliable results. The CUSUM and CUSUMSQ tests help to ensure the model's reliability by checking its stability over time. Latter tests determine if the model's parameters stay constant or if there are significant changes that could cause structural breaks. Meanwhile, the VIF test is checking the multicollinearity, measuring how much the variance of each independent variable is inflated due to correlation with other variables in the model.

3. Empirical results and discussion

Table 1 below explains the variable details and the sources of data.

Table 1. Details of selected indicators and the data sources (prepared by authors, 2024)

Variables	Detailed variables	Sources
PCO_2 emissions	CO_2 discharges per person (tons)	OWID (n.d.)
Industrialization	Value added as a percentage of Gross Domestic Product	World Bank Group (n.d.)
Consumption of self-renewing power	Proportion of primary energy use from self-renewing sources (%)	OWID (n.d.)
Economic progress	Gross Domestic Product per person (US$)	World Bank Group (n.d.)
Trade Openness	Total trade in services and goods as a percentage of Gross Domestic Product	World Bank Group (n.d.)

The primary variable of this research is carbon emissions, to be examined alongside other indicators as industrialization, consumption of self-renewing power, trade openness, and economic progress.

3.1. Model formulation to investigate both the long-term and short-term impact of industrialization, economic growth, renewable energy, and trade openness on CO_2 discharges in Indonesia

3.1.1. ARDL model framework to evaluate functional correlation among indicators

The general Eq. (1) represents the functional relationship between the chosen variables. This Equation is designed to predict how these variables influence each other and helps to formulate the ARDL model Equation based on these general Equations.

$$PCO_{2t} = f\left(INDU_t, REC_t, EG_t, TO_t\right), \quad (1)$$

where the variables at time t that represent CO_2 discharges, industrialization, consumption of self-renewing power, trade openness, economic progress are PCO_{2t}, $INDU_t$, REC_t, EG_t and TO_t respectively.

3.1.2. ARDL model formulation for long-term and short-term relationship

The ARDL model is incorporated in current research to examine the short and long-run relationships among the indicators. This method has been applied by different authors in a number of scientific works (Alam & Hossain, 2024). The ARDL method was explained by Pesaran and Shin (1995), and later developed by Pesaran et al. (2001). The present research investigates the short and long-term relationships, with calculations performed using E-Views 12 software, and can be obtained through the following source: (https://www.eviews.com/download/student12/). The following Equation (2) explains the ARDL bounds examination technique.

$$\Delta PCO_{2t} = \alpha_0 + \sum_{k=1}^{n}\alpha_1\Delta INDU_{t-k} + \sum_{k=1}^{n}\alpha_2\Delta REC_{t-k} + \sum_{k=1}^{n}\alpha_3\Delta EG_{t-k} + \sum_{k=1}^{n}\alpha_4\Delta TO_{t-k} + \lambda_1 INDU_{t-1} + \lambda_2 REC_{t-1} + \lambda_3 EG_{t-1} + \lambda_4 TO_{t-1}, \quad (2)$$

where Δ shows the 1st change, ε_t the white noise, and α_0 the component of drift. To investigate the lag period, the research applies the AIC (Akaike Information Criterion). For next investigation of the short-run impacts, the evaluation firstly applies the Error correction term (ECM) to explore the long-run correlation among indicators. The following presented Eq. (3) displays the ECM form in Eq. (2).

$$\Delta PCO_{2t} = \alpha_0 + \sum_{k=1}^{n}\alpha_1\Delta INDU_{t-k} + \sum_{k=1}^{n}\alpha_2\Delta REC_{t-k} + \sum_{k=1}^{n}\alpha_3\Delta EG_{t-k} + \sum_{k=1}^{n}\alpha_4\Delta TO_{t-k} + \varnothing ECM_{t-k} + \varepsilon_t, \quad (3)$$

where, for short-term interaction, ∅ means ECM coefficients, Δ – primary variation. Presented error-correcting model shows the value of long-run stability variation following a short-run shock.

3.2. Testing the stationarity of variables using unit root tests (ADF Unit Root Test)

ADF Unit Root Test is important before performing the ARDL bounds test. For the ARDL bounds test, it is required that each variable needs to be stationary and meet the requirement, which means each variable is stationary at the level I (0), first difference I (I), or mixed (some at the first difference I (I) and some at the level I (0)).

The present research uses the Unit Root Test tool for testing. The test results are shown in Table 2. The research results show that that PCO_2 emissions and industrialization are stable at the 1st difference and the level, while renewable energy consumption, economic progress and trade openness are stable at the 1st difference. Based on these test results, we can apply the ARDL bounds test.

Table 2. Augmented Dickey-Fuller (ADF) test results (prepared by authors, 2024)

Variables	ADF 1st level I(0)	ADF 1st difference I(I)
PCO_2 emissions	–4.1251 (0.0190)	–5.5287 (0.0012)
Industrialization	–3.8682 (0.0308)	–5.5656 (0.0008)
Renewable energy consumption	–1.4519 (0.8165)	–5.9688 (0.0004)
Trade openness	–3.1483 (0.1193)	–6.7152 (0.0001)
Economic growth	–1.6778 (0.7282)	–3.7269 (0.0418)

3.3. Checking the cointegration relationship among variables (ARDL Bounds Test)

The dataset's stationarity is determined using the ADF testing tool. To check the cointegration association existence of the relationship among variables – ARDL bounds test is utilized.

Table 3. ARDL Bounds Test results (prepared by authors, 2024)

F-Bounds Test	Estimate	Sign	I (0)	I (I)
F-Statistics	7.5233	10%	2.45	3.53
K = 4		5%	2.86	4.01
		2.5%	3.25	4.49
		1%	3.74	5.06

Calculation outputs of the ARDL bounds test are shown in the Table 3. Examined values: the lower and upper critical values are below in comparison with the calculated F-statistic of 7.5233 value. Current study concludes on the fact when indicators have a stable relationship.

3.4. The ARDL model technique: short and long-run results

ARDL model's calculation results are revealed in the Table 4. Current research identified negative and statistically relevant impacts of industrialization on Indonesian carbon discharges in the long and short periods. As per the calculations, a 1% boost in industrialization decreased 0.0310% (long-term) and 0.0389% (short-term) carbon discharges in Indonesia. The present research revealed considerable and positive correlation among renewable power usage as well as CO_2 discharges, indicating the information when a one percent growth in renewable power usage results in a 0.0309% (long-term), 0.0387% (short-term) growth in Indonesian's CO_2 discharges. Furthermore, trade openness shows a direct connection with carbon emissions, but the statistical level is insignificant. A one percent rise in trade openness results to a 0.0132 growth in carbon discharges over the long period, and a 0.0145 rise over the short term. However, the present research shows a positive and significant connection between economic progress and carbon discharges, indicating that a one percent growth in economic progress would add 0.0003% in the short-run, and 0.0002% to carbon discharges in the long-run.

Table 4. ARDL long-run & short-run results (prepared by authors, 2024)

Indicator	Long-Term			Short-Term		
	Coeff.	t-stats	p-value	Coeff.	t-stats	p-value
INDU	–0.0310	–2.5201	0.0227	–0.0389	–2.3282	0.0333
REC	0.0309	3.2714	0.0048	0.0387	2.7744	0.0135
TO	0.0132	2.3831	0.0299	0.0145	2.5826	0.0200
EG	0.0002	7.7683	0.0000	0.0003	5.4975	0.0000
ECT_{-1}				–1.2535	–6.8572	0.0000

The pace of adaptation from long and short-term balance is also shown by the ECM value. The computed ECM has a negative significant value, and the coefficient is statistically significant at the 1% level. As a result, the model's ECM value indicates that, annually, there is an average 125% correction to short-term variations that deviate from the long-run equilibrium trajectory. The statistically significant negative sign of the ECM coefficient indicates that any long-term disequilibrium among the model variables will migrate or converge to the long-term equilibrium.

Current research outcomes show that the industrialization has an adverse (negative) connection with carbon discharges in Indonesia. It reveals that the industry sector in Indonesia helps to reduce carbon emissions. Some previous research works have the same results as our research (Elfaki et al., 2022; Idowu et al., 2023; Ridwan et al., 2024). But our research results indicate that utilization of self-renewing power damage the surrounding environment in Indonesia. Some recent studies endorse our results (Altın, 2024; Apergis & Payne, 2009). Several factors support to the positive relationship among renewable power and CO_2 discharges in Indonesia, including costs, inadequate infrastructure, and storage challenges. Additionally, the Indonesian government has set an aspirational objective of reaching a 23% stake of renewable energy by 2025, yet it fell short in 2022 with a renewable energy share of just 12.3 (Badaskara et al., 2024). Similarly, the part of electric power production based on self-renewing power in Indonesia decreased from 19.61% in 2022 to 18.59% in 2023 (OWID), 2022). Meanwhile, trade openness shows a direct link with carbon emissions. In Indonesia, the trade openness factor damages environmental sustainability, necessitating a revision of trade policies to ensure they reduce the level of carbon emissions. Some research results support our research findings (Bagadeem et al., 2024; Mahmood et al., 2019). Likewise, economic progress leads to CO_2 discharges in Indonesia. Research findings demonstrated that a positive correlation have CO_2 discharges and economic progress in Indonesia. Some research works get similar results to ours, and these research findings are supportive (Adebanjo & Akintunde, 2024; Adebayo, 2024; Aldegheishem, 2024; Rigas & Kounetas, 2024).

3.5. Use of diagnostic tools to confirm the accuracy of research results

In the current investigation ARDL results validity was verified using different diagnostic tests. The Table 5 shows diagnostic testing. There isn't a serial relationship. The results of the BPG tool for heteroscedasticity showed absence of heteroscedasticity. The Applied Ramsey Rest Test confirmed that model is perfectly specified.

Table 5. Diagnosis tools: BGSC LM tool, BPG tool (Heteroscedasticity tool), RRT, CUSUM CUSUMSQ examination results (prepared by authors, 2024)

Evaluate	P-value	Decision
BGSC LM Test	0.1879	No sequential relationship
BPG Test (Heteroscedasticity Test)	0.5085	No existing heteroscedasticity
RRT	0.3121	The approach is perfectly defined
CUSUM	–	Stable
CUSUMSQ	–	Stable

By applying CUSUMSQ as well as CUSUM tools on the recursive residuals, this research in the ARDL approach additionally assesses the coherence of the short-term beta coefficients. At the 5% significant level, the CUSUM square and CUSUM tests' findings show no systematic conflict among dependent and independent indicators (Figure 2). Tests confirmed the stability of the model.

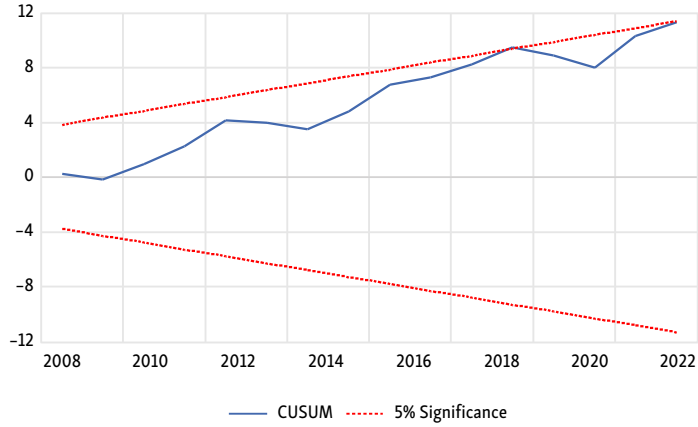

Figure 2. CUSUM test results (prepared by authors, 2024)

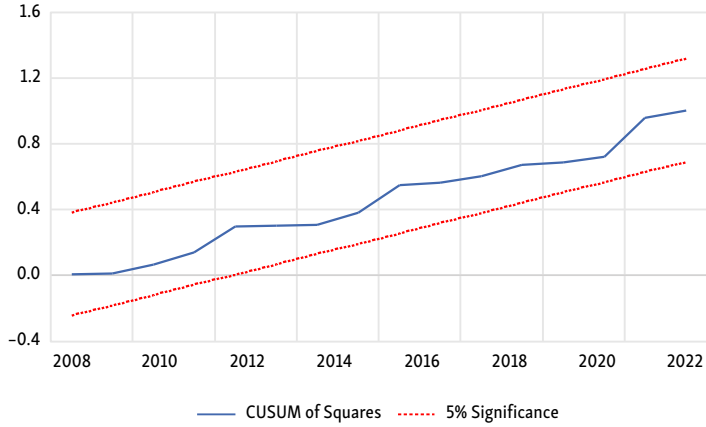

Figure 3. CUSUM of squares examination findings (prepared by authors, 2024)

Figure 2 shows that the CUSUM blue lines reside within the red upper and lower limits, confirming the model's stability and no structural break.

In the Figure 3 we see the results of CUSUM of squares tool reside inside the essential limits at a significance threshold of 5%, indicating absence of structural alterations and confirming stability of the model.

3.6. Checking for multicollinearity applying the VIF (Variance Inflation Factor) tool

This research uses the VIF tool to examine multicollinearity. The Table 6 shows the VIF test results, indicating that no multicollinearity is detected.

Table 6. VIF multicollinearity test results (prepared by authors, 2024)

Variable	Centered VIF
INDU	2.8026
REC	2.4176
TO	4.7862
EG	4.0930

This research uses the VIF test to detect multicollinearity among the independent indicators. Research findings are shown in the Table 6. If independent variables are correlated, VIF assesses the extent to which the variance of calculated regression coefficient rises. A general guideline is that if the VIF result is above 10, it indicates the presence of multicollinearity issues. Test results show that all VIF values are below 10, in line with the rule of thumb. Consequently, there are no serious issues of multicollinearity, and the results of the model are valid.

The aim of this study is to analyze the short and long-term – influence of industrialization, self-renewing power usage, economic progress, trade openness, and carbon discharges in Indonesia from 2000 to 2023. The ARDL Bounds test indicates the fact: the indicators are jointly integrated, and a long-term correlation exists among variables. Findings after application of the ARDL model demonstrate that industrialization has a negative correlation with CO_2 emissions. In Indonesia, the industrial sector contributes to increased environmental sustainability, which may result from the implementation of cleaner and green solutions. However, the impact influence of industrialization differs from nation to nation, depending on the nature of economic activities. Moreover, self-renewing power utilization unexpectedly shows a direct correlation with CO_2 discharges. Although previous studies suggest that renewable energy contributes to environmental sustainability, this study does not support that view – possibly due to limited adoption, storage issues, high costs, as well as the application of mixed power alternatives. Additionally, economic progress with trade openness have a positive relationship with carbon discharges. As Indonesia continues to grow economically (including expansion in tourism and increased foreign direct investment) and becomes more globally integrated, environmental pressures rise as a result of greater energy consumption together with manufacturing.

4. Conclusions

An investigation of the impact of industrialization, renewable energy consumption, economic growth and trade openness on CO_2 emissions during the period from 2000–2023 (24 years) was conducted on the case of Indonesia. Analysis showed that in the modern era the effect of industrialization, renewable energy consumption, economic growth and trade openness on CO_2 emissions is mixed. This research finds that industrialization increases the level of environmental sustainability, while self-renewing power consumption harms the environment's sustainability. Similarly, trade openness and economic growth also negatively affect environmental quality. At the same time, in the ASEAN region, Indonesia is increasing the level of its industrial sector and development, but this is also contributing to higher emissions levels.

The model to evaluate the short and long-term interactions among industrialization, renewable power utilization, trade openness and economic progress variables on carbon discharges in certain country (in this case – Indonesia) economics was developed employing the ARDL econometric technique. In order to investigate the short and long-term impact, the approach of ARDL tool was used. This technique examines the short and long-term relationships among industrialization, renewable power utilization, trade openness, economic progress, and carbon discharges. The ADF tool reveal these results: the research indicators (CO_2, industrialization, renewable energy, trade openness, economic progress) are stable at both the levels (meaning the data is stationary and doesn't have a trend over time) and the first difference (the changes in the data are stable, with no upward or downward trend). Furthermore, the ARDL Bounds test confirms that the indicators exhibit cointegration and maintain a long-term interaction among the research indicators (if the F-statistic is above the maximum and minimum bounds, the indicators exhibit cointegration and maintain a long-term connection). Once latter requirements are met, the ARDL approach is able to be implemented. This research integrates various diagnostic tools to enhance the accuracy of the findings. The Breusch-Godfrey tool examines residuals for serial dependence in the model, ensuring the model is correctly specified and no correlation is found. The BPG test detects non-homogeneous variance and confirms the reliability of standard errors of the model, with no issues found in this research model. The RRT tool evaluates the accuracy of the correlation between variables. When the CUSUMSQ and CUSUM tools assess the stationarity of the model over time and confirm consistency and error-free state of the model. Lastly, the VIF tool assesses the interdependence of variables to verify that the independent variables are not highly correlated, and no multicollinearity is found between variables.

The research has evaluated the short and long-term impact among indicators and CO_2 discharges in Indonesia.

This research identified whether industrialization and self-renewing power utilization have a positive and/or negative influence on environmental sustainability and economic progress in Indonesia. The findings indicate a negative correlation among industrial development and CO_2 discharges, meaning that industrial development has a positive influence for environmental sustainability in Indonesia. These results are supported by data of the World Bank Group, which show a significant rise in Indonesia's industrial growth over the past few years. On the

other hand, renewable energy consumption is directly associated with carbon discharges. The research findings showed that self-renewing power utilization adversely influences on sustainable ecology in Indonesia.

Based on the research findings, several policy recommendations are made. Short-term strategy: immediate focus should be placed on reducing fossil fuel dependency, especially coal, which currently accounts for over 62% of electricity generation. Policymakers should strengthen the monitoring and regulation of trade-related emissions, as trade activities also support the rise in CO_2 discharges in the country. Additionally, the efficiency of renewable energy systems should be improved, and fossil fuel projects should be replaced with renewable energy alternatives. Long-term strategy: The focus should be on enhancing industrial modernization and promoting green innovation. Green electric power can have a beneficial impact decreasing CO_2 discharges. Policymakers should address infrastructure bottlenecks such as off-grid accessibility, fragmented grids, and limited financing. Policies must be designed to reduce investment costs, which in 2022 were significantly higher than in peer countries – 65% higher than in India and 10% higher than in Thailand. Policymakers should introduce policies to shift energy reliance away from fossil fuels by providing subsidies and loans for solar, wind, and hydro technologies. Additionally, trade policies must incorporate environmental safeguards and enforce emissions standards in both production and export sectors.

The current research has a few limitations in a number of indicators and in selection of one country as the case study. Future research might include additional factors, such as energy usage specific, fossil fuels consumption, foreign direct investments, institutional quality, education and tourism, as well as another carbon emissions proxy based on territory and consumption. Future research papers may also consider using alternative proxies for emissions, such as consumption-based or territorial emissions. Additionally, future studies should explore why renewable energy still shows a positive correlation with emissions – possibly by disaggregating different types of renewable energy or examining the effectiveness of existing policies.

Authors contribution

The authors contributed to the elaboration of this research as next: Lidija Kraujalienė (50%), Atif Yaseen (40%), Inga Bilinskienė (10%).

Disclosure statement

Authors have no competing financial, professional, or personal interests from other parties.

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