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Do Economic Growth and Urbanization Drive CO_2 Emissions? Role of Renewable Energy and Energy Efficiency in Indonesia

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ABSTRACT

This study aims to investigate whether the damaging impact of rapid urbanization and economic growth on the environment is evident in the case of Indonesia while simultaneously looking at the role of renewable energy and energy efficiency. The current study utilizes yearly data (1991–2021) to establish the Augmented Environmental Kuznets Curve (EKC) model. For the method, an Autoregressive Distributed Lag (ARDL)-Bounds testing, Toda-Yamamoto (TY) causality, and Zivot-Andrews (ZA) test are employed. As the result of that cointegration is evidence, urbanization is verified as a driver of environmental degradation since it is positively connected to CO_2. Energy intensity is found to have a positive impact on CO_2; hence, increasing energy efficiency is pivotal. Renewable energy is confirmed to have a vigorous role in reducing emissions since it is negatively linked to CO_2. The association between per capita income and CO_2 is found to follow an inverse U-shaped, as suggested by the EKC hypothesis, showing that economic growth can be applied as an instrument for sustainable development. Bidirectional causalities are predominant among the observed variables. Following the findings, fostering energy transition by enhancing clean energy use while simultaneously improving energy efficiency is a crucial scheme to reduce CO_2 emissions in Indonesia.

Keywords: CO_2, Economic Growth, Urbanization, Renewable Energy, Energy Intensity
JEL Classifications: Q43, Q56, R11

1. INTRODUCTION

The vast majority of emerging economies such as Indonesia tend to showcase impressive economic growth rates, as well as rapid urbanization, driven by serval factors such as industrialization, natural resource extraction, infrastructure development, and government reform. Whilst economic growth and urbanization imply the process of development, both variables are connected to numerous types of environmental degradation, including carbon dioxide (CO_2) emissions (Sikder et al., 2022). Developing countries, generally, tend to neglect the damaging impacts of economic growth and rapid urbanization on the environment quality since they tend to prioritize output growth, poverty reduction, and job creation (Liang et al., 2019; Zhang et al., 2024; Turok et al., 2023).

Economic growth and urbanization are debated as underlying drivers of environmental degradation but the impacts are varied across regions (X. Wang and Zhou, 2023; Yansui et al., 2016). Demand for energy-intensive products rises in response to an increase in per capita household income, especially for food, transportation, and lighting (Li and Lin, 2015). This pattern, in turn, contributes significantly to air pollution. Previous study by Liddle (2015) noted that a 1% increase in per capita income leads to around a 0.81% increase in CO_2. However, the Environmental Kuznets Curve (EKC) proposes that the nexus between income and CO2 is non-monotonically increasing: Instead, it follows the inverse U-shaped or N-shaped patterns (Soberon and D’Hers, 2020; Fakher et al., 2023; Churchill et al., 2018)

Regarding the impact of urbanization on the environment, it is hypothesized that rural-urban migration and natural urban population growth produce CO_2 emissions from several types of activities, including consumption and production. Compared to rural communities, urban people consume more fossil energy for lighting, cooking, and cooling, which in turn contributes to higher CO_2 emissions (Krey et al., 2012; Nie et al., 2024). In addition, urban areas are likely to be warmer than rural areas due to the heat-absorbing properties of buildings and the lack of green spaces (Nie et al., 2024). This can lead to increased energy consumption for cooling, further exacerbating CO_2. Furthermore, urbanization tends to be followed by industrialization which can significantly impact air pollution through operation processes (Raheem and Ogebe, 2017).

Urbanization is also linked to industrialization, which is designated by low energy efficiency, high energy usage, and high emissions (Wang et al., 2016). Rural-urban migration and natural urban population growth also drive urban sprawl which massively generates CO_2 through land use change. An empirical study by Shahbaz et al. (2016) found that urbanization initially reduces CO_2 emissions, but at the threshold level, it switches to intensify the ones. Conversely, Gierałtowska et al. (2022) revealed that the nexus between urbanization and CO_2 follows an inverse U-shaped, showing that urbanization has a potential role in supporting sustainable development. Moalla (2024) recorded that urbanization is positively associated with CO_2 in the short-run but it is negatively connected to the long-run ones. Furthermore, Wang et al. (2021) noted that the damaging impact of urbanization on the environment is not verified in developed countries.

Whilst detrimental effects of rapid urbanization and economic growth on the environment are observed; it is argued that transitioning toward clean energy can lessen this damage. Renewable energy is a substitution generator for fossil fuels. Thus, promoting renewable energy generators, i.e., wind, solar, and hydropower, will lead to a decline in emissions. Prior studies have validated the crucial significance of eco-friendly energy in lowering CO_2 (Waheed et al., 2018; Dong et al., 2017). Nonetheless, Pata et al. (2023) remarked that the beneficial role of clean energy in reducing emissions in the case of the Association of Southeast Asian Nations (ASEAN) countries is only verified in the short run. Furthermore, Ben Jebli and Ben Youssef (2017) found that renewable energies, i.e., combustible and waste, are positively linked to emissions. Kilavuz and Doğan (2021) reported a U-shaped connection between green energy and CO_2 in developing countries. Hence, the role of renewable energy on the environment remains under debate as there are numerous types of clean energy generators and environmental degradation indicators.

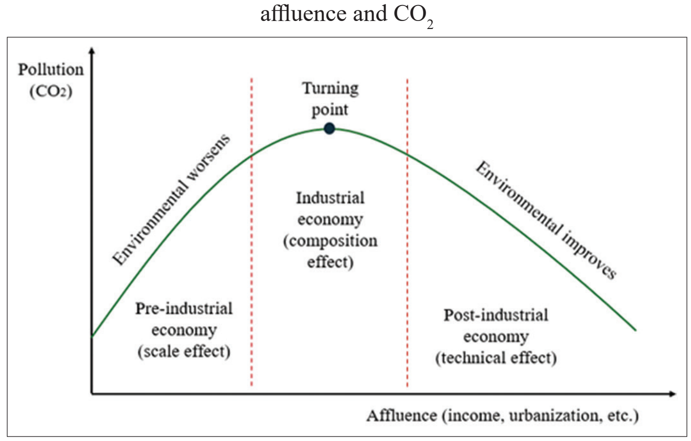
Against the background above, this study intends to explore the damaging impact of urbanization and economic growth on the environment while simultaneously unraveling the role of renewable energy and energy efficiency in the case of Indonesia using yearly data spanning from 1991 to 2021. This study adopts the augmented version of the EKC model to check whether the non-linear nexus between income and CO_2 is verified in Indonesia. Hence, research questions are specified as follows: (i) is the EKC hypothesis evident? (ii) if evidence, how much is the monetary value of the EKC turning point and its relevance? (iii) does urbanization exert a detrimental influence on the environment by raising CO_2 emissions? (iv) is the beneficial effect of renewable energy in reducing CO_2 verified? To provide nuanced empirical findings, several econometric methods are employed, including regression, causality test, and stationary test.

This study proposes empirical and methodological novelties as follows: first, this study provides empirical evidence for the causal relationship between income, urbanization, energy, and CO_2 emissions in the case of Indonesia, estimating dynamic short-and-long-run elasticities, as well as causal direction. Second, instead of using the conventional stationary test, the breakpoint approach (Zivot-Andrews test) is employed to ascertain the order of integration. It should be noted that the vast majority of macroeconomic variables in the case of developing tend to have unit roots such as trends, random walks, or structural breaks. Third, the current study utilizes a causality method that accommodates nonstationary series, namely the Toda-Yamamoto (TY) test. To the best authors' knowledge, most earlier studies in the context of Indonesia rely on a conventional method the Granger Causality (GC) approach (Shahbaz et al., 2013; Bashir et al., 2021; Bashir et al., 2019). Last of all, to check consistency findings, this study includes multiple-stage regressions using Ordinary Least squares (OLS) for the robustness of ARDL estimates.

2. LITERATURE REVIEW

The impact of economic growth and urbanization on environmental quality indicators, including CO_2 emissions, can be rigorously investigated using the EKC framework. Compared to the STRIPAT model, the EKC hypothesis is relatively more sophisticated since it allows scholars to examine the presence of a non-linear relationship. Instead of monotonically increasing, the association between affluence and emissions may exhibit an inverse U-shaped pattern as displayed in Figure 1. Therefore, the EKC model proposes that economic growth can be negatively or positively associated with emissions, depending on the stage of development, the adoption of technology, and consumer preferences (Rashid Gill et al., 2018).

Figure 1: An illustration of the inverse U-shape linkage between affluence and CO_2



Source: (Ben Jebli et al., 2022; Xie et al., 2019), modified

Whilst the EKC hypothesis is mostly verified, the income turning point can significantly vary across countries because numerous factors, including social and economic, affect the trajectory of environmental quality (Dong et al., 2017; Jaeger et al., 2023). For instance, Uchiyama (2016) found that a global turning point is around 30,000 USD per capita, and there is a variation in turning points between developing and developing economies. A meta-analysis conducted by (Sarkodie and Strezov, 2019) reported that the EKC threshold is 8,900 USD per capita. A literature review conducted by AlKhars et al. (2022) recorded that, over the period 2010-2020, 62 articles supported the EKC hypothesis while 57 articles contradicted the inverse U-shaped connection.

Rafindadi (2016) tested the nexus between income and CO_2 in an advanced economy, i.e., Japan, by integrating trade and energy consumption. His findings suggest that the EKC hypothesis is verified, and energy is a major driver of environmental degradation. By disregarding the supply-side dynamic in the EKC model, Ali et al. (2024) confirmed the EKC hypothesis for Canada. The inverse U-shaped connection of income and emissions, as well as the beneficial role of renewable energy, is also verified in highly globalized countries (Mirziyoyeva and Salahodjaev, 2023). Empirical study by Koshta et al. (2021) uncovered the EKC model and Resource Curse Hypothesis (RCH), a negative association between natural resource endowment and economic growth, in emerging economies.

In the context of Indonesia, Sugiawan and Managi (2016) tested the damaging impact of economic growth on pollution by employing yearly data from 1980 to 2010 and considering the impact of clean energy. Their findings recorded that the EKC hypothesis is evident, and renewable energy is verified to be adversely associated with emissions. Correspondingly, Leonardo et al. (2023) verified EKC and pollution heaven hypotheses, a positive linkage between CO_2 and trade openness. Using a similar vein, Massagony and Budiono (2023) investigated the EKC hypothesis by integrating the impact of fossil energy, renewable energy, and forest moratorium and restoration policies. The inverse U-shape association is not validated, implying that CO_2 emissions will continue to increase simultaneously with income.

Using panel data from 106 countries, Lawson et al. (2020) revealed that the EKC hypothesis is not accepted, while a convergence process is taking place, indicating that current international accords have not been sufficiently binding to curb emissions. Similarly, Aye and Edoja (2017) found that the inverse U-shaped association between income and CO_2 emissions is not validated in developing countries. Furthermore, Alola and Donve (2021) reported the absence of the EKC hypothesis and the damaging impact of coal and oil energies in Turkey. Koc and Bulus (2020) revealed the N-shaped pattern between income and CO_2 in South Korea, showing the absence of the EKC framework. Nonetheless, it was verified that trade openness and renewable energy play a crucial role in assisting CO_2 reduction.

3. METHODS

3.1. Model Specification

Following the EKC hypothesis, the initial model can be formulated as Eq. 1

$$CO_{2t} = \vartheta_0 + \vartheta_1 YN_t + \vartheta_2 YN^2 + \varepsilon_t \tag{1}$$

Where in CO_2 denotes CO_2 emissions. YN and YN^2 signify GDP per capita and GDP per capita squared, respectively. Based on Eq. 1, there are five possible relationships between income and CO_2 (Table 1).

Supposed the EKC is validated ($\vartheta_1 > 0$ and $\vartheta_1 < 0$), the income-emissions turning point can be calculated using Eq. (2)

$$T^*_{EKC} = \exp\left(-\frac{\vartheta_1}{2\times\vartheta_2}\right) \tag{2}$$

By integrating the impact of urbanization, renewable energy, and energy intensity, Eq. 1 is rewritten as Eq. 3.

$$CO_t = \vartheta_0 + \vartheta_1 YN_t + \vartheta_2 YN^2 + \vartheta_3 URB_t + \vartheta_4 EIN_t + \vartheta_5 REN_t + \varepsilon_t \tag{3}$$

Where in URB, EIN, and REN signify urbanization, energy intensity, and renewable energy. ε_t is the constant term, and it is assumed to be IID. The expected value of ϑ_5 is negative, showing the beneficial impact of renewable energy in reducing CO_2 emissions. Conversely, the expected signs of ϑ_3 and ϑ_4 are positive, denoting the damaging impact of urbanization and inefficient energy consumption.

3.2. Econometric Methods

This study employs several econometrics methods to deeply understand the dynamic relationship between CO_2 and economic growth under the ECK hypothesis while concurrently adding the impact of energy intensity and renewable energy consumption in Indonesia.

3.3. Stationary Test

In the case of developing countries, macroeconomic data tend to exhibit unit root processes namely trend or random walk component. Accordingly, it is critical to examine the order of integration. In addition, the stationary test is a necessary step because the ARDL is no longer proper for application if variables are second-order integration. For this reason, the current study relies on the ZA test. Compared to the conventional method, i.e., the Dickey-Fuller (DF) test, the ZA test is chosen since it can be

Table 1: Five possible forms of the nexus between income and CO_2

Types of relationship	ϑ_1	ϑ_2
No relationship	Zero (ϑ_1=0)	Zero (ϑ_2=0)
Positive monotonic	Positive (ϑ_1>0)	Positive (ϑ_2>0)
Negative monotonic	Negative (ϑ_1<0)	Negative (ϑ_2<0)
inverted U-shaped	Positive(ϑ_1>0)	Negative (ϑ_2<0)
U-shaped	Negative (ϑ_1<0)	Positive (ϑ_2>0)

Source: (AlKhars et al., 2022)

used to check the presence of unit roots under structural breaks. The ZA test deals with the breakpoint (TB) endogenous factors. A general equation for the ZA test is:

$$\Delta x_t = \mu + \phi DU_t + \beta t + \vartheta DT_t + \alpha x_{t-1} + \sum_{j=1}^{k} \eta_j \Delta x_{t-1} + \epsilon_t \quad (4)$$

Where in DU_t and DT_t stand for dummy variables for a mean shift and a trend shift, respectively. $DU_t = 1$ if $t > T_B$ and 0 otherwise; $DT_t = t\text{-}T_B$ if $t > T_B$ and 0 otherwise. The year breakpoint is estimated by employing the ordinary least squares for t = 2,…. T-1. Therefore, the (T-2) regression model will be computed, and the year breakpoint is defined by the minimum t-statistic on the parameter of the autoregressive (AR) variable t_α).

3.4. ARDL-Bounds Testing

The ARDL-Bounds test is applied to produce the dynamic short-run and long-run associations between CO_2 and its set of explanatory variables. The ARDL-Bounds testing is an unbiased estimator and can be used for a small sample size. Previous studies also worked with the ARDL-Bounds testing. Following Eq. 3, the ARDL (p,q_n) model is written as Eq. (5)

$$\begin{aligned}\Delta CO_{2t} = {} & \vartheta_0 + \sum_{i=1}^{p} \vartheta_1 CO_{2t-i} + \sum_{i=0}^{q} \vartheta_2 YN_{t-i} + \sum_{i=0}^{q} \vartheta_3 YN_{t-i} \\ & + \sum_{i=0}^{q} \vartheta_4 URB_{t-i} + \sum_{i=0}^{q} \vartheta_5 REN_{t-i} + \sum_{i=0}^{q} \vartheta_6 REN_{t-i} \\ & + \lambda_1 CO_{t-i} + \lambda_2 YN_{t-i} + \lambda_3 YN_{t-i} \\ & + \lambda_3 URB_{t-i} + \lambda_4 EIN_{t-i} + \lambda_5 REU_{t-i} \\ & + \; + \;_{t\ i} \end{aligned} \quad (5)$$

The long-run estimators, i.e., $\lambda_1 ... \lambda_5$, are meaningful to be interpreted only if there is cointegration. The ARDL-Bounds test relies on joint F-statistics to check the presence of cointegration. The null hypothesis, H0: λ_1=□=λ_5=0 is tested against the alternative hypothesis, H1: λ_1=□=$\lambda_5 \neq 0$. Reject the H0 if the estimated f-statistics exceed the upper bound, I[1]. Otherwise, there is no level relationship. In the case of a small sample, the F-test relies on the F-table produced by (Narayan, 2005). As an alternative, Sam et al. (2019) offered the additional F-test regardless of requiring that the dependent variable is $I(1)$

Supposed there is cointegration; hence, the error correction model is written as Eq. (6)

$$\begin{aligned}\Delta CO_{2t} = {} & \vartheta_0 + \sum_{i=1}^{p} \vartheta_1 CO_{2t-i} + \sum_{i=0}^{q} \vartheta_2 YN_{t-i} + \sum_{i=0}^{q} \vartheta_3 YN_{t-i}^2 \\ & + \sum_{i=0}^{q} \vartheta_4 URB_{t-i} + \sum_{i=0}^{q} \vartheta_5 EIN_{t-i} + \sum_{i=0}^{q} \vartheta_6 REN_{t-i} \\ & + \varpi ECM_{t-1} + e_{t-i} \end{aligned} \quad (6)$$

Where in the parameter ϖ represents the speed of adjustment. ϖ must have a negative sign (0 – 2) and be statistically significant. Shock that caused short-run deviation is adjusted toward long-run equilibrium. Additionally, this study includes diagnostic and stability tests to ensure reliable and valid findings.

3.5. Toda Yamamoto

This study works with the TY causality test to examine the cause-and-effect analysis between CO_2, YN, URB, EIN, and REN. Despite a conventional method the Granger Causality (GC) test, the TY causality approach is performed because it is more relaxed in terms of the order of integration. It is proper for level, $I(0)$ and first-order integration, $I(0)$ (Kumar et al., 2015). The TY test consists of two critical stages: defining the maximum lag order (d) and determining the maximum lag length (k) (Sharaf et al., 2024; Amiri and Ventelou, 2012). Hence, the VAR (k+d) model is used to estimate causal relationships. A general augmented VAR system can be written as Eqs. (7) and (8) (Toda and Yamamoto, 1995).

$$Y_t = v_1 + \sum_{i=1}^{k+d} \vartheta_{1i} Y_{t-i} + \sum_{i=1}^{k+d} \theta_{1i} X_{t-i} + e_{1t} \quad (7)$$

$$Y_t = v_2 + \sum_{i=1}^{k+d} \vartheta_{2i} X_{t-i} + \sum_{i=1}^{k+d} \theta_{2i} Y_{t-i} + e_{12} \quad (8)$$

Wherein X and Y represent model variables. The d term denotes the maximum order of integration; the term k term signifies the optimal lag length. e_{1t} and e_{2t} depict residuals. Several previous EKC studies also employed the TY test to check the causal direction (Manisha et al., 2023; Pata and Aydin, 2020; Eweade et al., 2024)

4. EMPIRICAL RESULTS

To begin with the findings and discussion, Table 2 provides the results of unit root tests in the level and first difference. The ZA test is applied to accommodate structural breaks. The results suggest that CO_2, YN, and EIN are stationary at their level, denoting that they are integrated of order zero, $I(0)$. Other variables, that is, URB and REN, fail to reject the H0 a 5% critical value. Thus, URB and REN are nonstationary at their levels. Nonetheless, they are stationary after the first difference is taken into account. It can be inferred that URB and REN are integrated of order one, $I(1)$. Given that none of the variables are identified as second-order stationary, $I(2)$, the ARDL-bounds test is appropriate to examine the dynamic short-run and long-run associations between CO_2, YN, YN^2, REN, URB, dan EIN.

The next step before the application of the ARDL-Bounds testing is to determine the optimal lag order. As shown in Table 3, the FPE, AIC, and HQIC statistics recommend that the optimal lag length is two (p=2). However, the SBIC statistics suggest that the optimal lag length is one (p=1). Thus, it is acceptable to specify order 1 or 2 for the maximum lag in ARDL-Bounds testing. Figure 2 depicts the top 20 ARDL models as suggested by the BIC. The findings conclude that ARDL (1,1,0,0,0,1) is the most efficient model. As a consequence, the dynamic short-run and long-run parameters in this study rely on the ARDL (1,1,0,0,0,1) model..

4.1. Cointegration Test

Having determined the order of integration, the next discussion is to explore the presence of level relationships using the Bounds test.

Table 2: Zivot-Andrews test results

Variable	Level	k	*T**	FD	k	*T**
With intercept						
CO_2	−4.748*	1	2004	−6.253***	1	2017
YN	7.528***	0	1998	−4.768*	0	1998
URB	−2.928	1	1997	−9.447***	0	2001
REN	−3.584	0	2011	−7.291***	0	2009
EIN	4.838**	1	1998	−4.862**	0	2004
Critical values: 1%: −5.34, 5%: −4.80, 10%: −4.58						
With intercept and trend						
ΔCO_2	−5.552**	1	2015	−6.605***	1	2018
ΔYN	−7.397***	0	1998	−5.595***	0	2000
ΔURB	−3.852	1	1998	−14.637***	0	2001
ΔREN	−3.564	0	2011	−7.142***	0	2009
ΔEIN	−5.112***	1	1998	−5.166**	0	2000
Critical values: 1%: −5.57, 5%: −5.08, 10%: −4.82						

k denotes the selected lag, *T** shows the year break point. FD stands for the first difference

Table 3: Lag length test results

Lag	FPE	AIC	HQIC	SBIC
0	2.20E-16	-19.0273	-18.9387	-18.7444
1	3.10E-22	-32.5605	-31.9403	-30.5803*
2	2.1e-22*	-33.282*	-32.1302*	-29.6044

Endogenous: $LnCO_2$, LnYN, LnYN2, LnURB, LnRE, LnEIN
*signifies lag order selected at a 5% level of significance. FPE: Final prediction error; AIC: Akaike information criterion; SBIC: Schwarz information criterion; HQIC: Hannan-Quinn information criterion.

The results of the Bounds test are presented in Table 4. The H0 of no cointegration relationship must be rejected since the estimated F-statistic (21.717) exceeds the upper critical bounds (4.15) at a 1% critical value. Thus, there is no potential spurious regression. Instead, there is a long-run relationship between CO_2, economic growth, urbanization, renewable energy, and energy intensity.

4.2. Long-run and Short-run Relationship

Table 5 presents the results of long-term ARDL estimates. The positive YN and negative YN^2 parameters indicate the presence of the EKC hypothesis in the case of Indonesia in the long run. In other words, the nexus between economic growth and CO_2 is non-linear; instead, it exhibits an inverse U-shaped association. This finding is consistent with prior investigations in Turkey (Kilavuz and Doğan, 2021), Italy (Baiardi, 2014), Indonesia (Adebayo, 2020), Malaysia (Jahanger et al., 2022), China (Chang et al., 2021), and Brazil (Freire et al., 2023). The existence of the EKC hypothesis implies that an increase in income initially led to an increase in CO_2; however, after a certain point, it led to a decrease in these emissions. The monetary values of tipping points can be estimated as follows:

$$T^*_{EKC} = \exp\left(-\frac{\beta}{2\beta}\right) = \exp\left(-\frac{7.76}{-0.90}\right) = 5479.39$$

The estimated turning point (T^*_{EKC}) is 5,040.497 USD per capita, which is outside of observation. However, this monetary figure is reasonable since the principle of sustainable development may still not be fully achieved by Indonesia. The presence of the EKC hypothesis indicates that the transition toward a cleaner economy is experiencing in Indonesia. As stated by Iwata et al. (2010), the income-CO_2 tipping point in developing countries may be outside the period of observation. Since Indonesia has not yet reached its EKC threshold, current output growth is associated with an increase in CO_2 emissions.

Table 4: Bounds test results

Test stat.	Value	Sign.	[1_0] (lower bound)	[1_1] (upper bound)
F	21.717	10%	2.08	3.00
t	-7.479	5%	2.39	3.38
k		2.50%	2.70	3.73
		1%	3.06	4.15

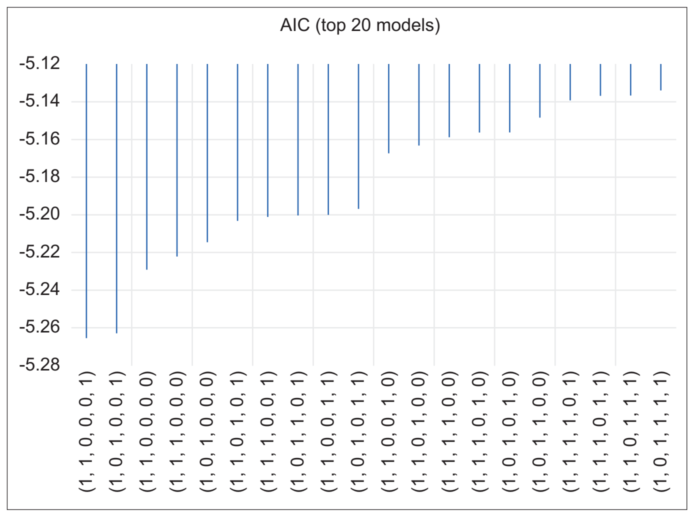
k shows the number of explanatory variables

Table 5: Long-run ARDL estimates

Dependent: $LnCO_2$ (1,1,0,0,0,1)				
Variable	**Coeff.**	**Std. error**	**t-stat.**	**p-value**
LnYN	7.95135***	2.08664	3.81	0.001
LnYN2	-0.46634***	0.14263	-3.27	0.004
LnURB	0.70553***	0.14768	4.78	0.000
LnIEN	0.56406***	0.13611	4.14	0.000
LnREN	-0.37352***	0.12599	-2.96	0.007
Constant	-28.93681***	7.20746	-4.01	0.001

***p<1%

Figure 2: ARDL model selection



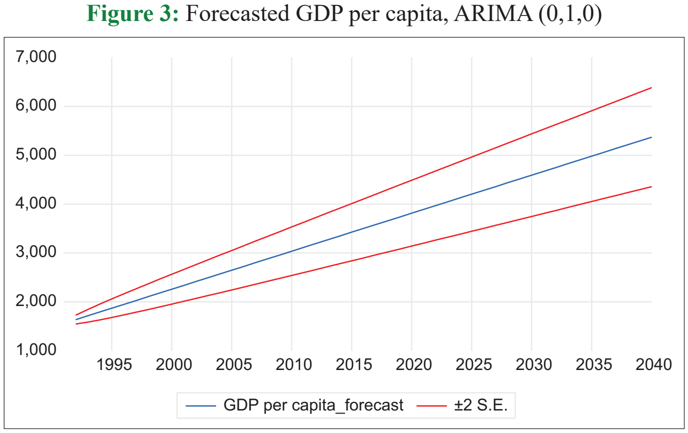
By integrating the Autoregressive Integrated Moving Average (ARIMA), it is possible to forecast the precise year for Indonesia to attain its income turning point. ARIMA is the proper statistical method for forecasting in cases where variables are nonstationary. Based on information collected from autocorrelation and partial correlation functions, ARIMA (0,1,0) is the best model as it has the lowest AIC compared to alternative models. ARIMA (0,1,0) indices a random walk process, the absence of autoregressive or moving average terms. Figure 3 presents the forecasted GDP per capita for Indonesia. According to the findings, Indonesia is expected to reach 5,040.497 USD per capita (constant 2015 US$) by 2036.

Next, urbanization is found to have a positive and significant effect on CO_2. This finding aligns with previous works by Cui et al. (2022) for China, Shahbaz et al. (2016) for Malaysia, and Bashir et al. (2021) for Indonesia. As mentioned by Lin et al. (2017) the effect of urbanization on emissions is likely to be more significant in developing countries than in advanced economies. Urbanization is verified as a driver of environmental degradation in Indonesia. This indicates that policymakers did not manage both natural urban population growth and rural-urban migration sustainably, so they contribute significantly to air pollution. TThe estimated parameter suggests that a 1% rise in the share of urban inhabitants drives a 0.71% increase in CO_2 levels, ceteris paribus. Theoretically, urbanization can directly and indirectly affect the environment. This evidence indicates that the damaging impact of urbanization on air quality, particularly through fossil fuel consumption and land use change, outweighs the benefits of technological improvement, efficiency, and innovation that come with urban agglomeration (Tang and Hu, 2023). Thus, it is crucial to promote sustainable urban development in Indonesia.

Another novel finding is that renewable energy use has a negative and significant impact on CO_2. This finding corroborates previous studies by Jaforullah and King (2015) for the United States (US), Sasana and Aminata (2019) for Indonesia, and Koshta et al. (2021) for emerging economies. Hence, clean energy is confirmed to offer a beneficial role in driving CO_2 in Indonesia. Wang et al. (2021) remarked that the CO_2 mitigation effect of the increase in the share of clean energy usage is considerably higher than that of technological improvements from renewables. The estimated parameter implies that holding other factors constant, a 1% rise in renewable energy corresponds to a 0.37% decrease in CO_2 levels. This finding emphasizes the need for energy transition. The bright side is that Indonesia has a host of massive renewable energy resources, including geothermal, hydropower, biomass, solar PV, windrower, and ocean energy (Langer et al., 2021). As clean energy is negatively associated with CO_2, ramping up renewable energy technologies might accelerate the EKC tipping point.

The last explanatory variable, energy intensity, is positively associated with CO_2 at a 1% critical value. This finding is consistent with several past studies in China (Lin et al., 2017), the US (Danish et al., 2020), and selected African countries (Shahbaz et al., 2015). The estimated coefficient implies that a 1% increase in energy intensity leads to a 0.48873 increase in CO_2. It should be noted that higher energy intensity indicates that an economy is less efficient regarding energy consumption. In order words, the amount of energy burned is relatively high

Figure 3: Forecasted GDP per capita, ARIMA (0,1,0)



compared to the output produced. Thus, it is crucial to promote energy efficiency. Additionally, a positive association between energy intensity and CO_2 also suggests that Indonesia relies more heavily on fossil fuels.

Regarding short-run relationships, Table 6 presents the estimated parameters. Whilst the short-run ARDL-Bounds testing generally focuses on the ECM parameter, it is important to highlight the explanatory variables. The EKC hypothesis is validated in the short run since ΔLnYN is positively associated with CO_2 whereas $\Delta LnYN^2$ is negatively associated with CO_2. The damaging impact of urbanization is also verified in the short run. A 1% increase in the urbanization corresponds to a 0.75% rise in CO_2 levels. Energy intensity has a negative effect on CO_2 as expected. A 1% increase in energy intensity will be associated with a 0.60% escalation in CO_2, showing an inelastic relationship. Conversely, renewable energy has an adverse impact on CO_2 as hypothesized. This implies that the expansion of clean energy immediately leads to emissions reduction. Importantly, shocks that caused a deviation in the short-run will be adjusted toward long-run equilibrium since the ECM parameter has a negative sign, <|-2|, and is statistically significant. This evidence also corroborates the Bounds test. The estimated ECM coefficient is 1.06, indicating that the pace of adjustment toward long-run equilibrium is less than 1 year.

4.3. Diagnostic and Stability Tests

To ensure the validity and reliability of ARDL-Bounds testing estimates, this study integrates a set of diagnostics tests. These estimations include the Breusch-Godfrey, Glejser, Ramsey RESET, and Jarque-Bera (JB) tests, and the results are jointly presented in Table 7. The Breusch-Godfrey test denotes that the model is free from serial correlation. Furthermore, the computed statistics in the Glejser and Ramsey tests confirm that the problems of heteroscedasticity and omitted variables are not evident. Following the JB test, error terms are observed to adhere to a normal distribution.

In addition to the diagnostic test, this study integrates model stability tests. For this motivation, the cumulative sum of recursive residuals (CUSUM) test is applied. As displayed in Figures 4

Table 6: Shor-run ARDL estimates

Dependent: $\Delta LnCO_2$ (1,1,0,0,0,1)				
Variable	**Coeff.**	**Std. error**	**t-stat.**	**p-value**
ΔLnYN	8.02496***	2.71976	2.95	0.008
ΔLnYN2	-0.49532**	0.18218	-2.72	0.013
ΔLnURB	0.74938***	0.22137	3.39	0.003
ΔLnEI	0.59911***	0.12542	4.78	0.000
ΔLnREN	-0.55352***	0.11502	-4.81	0.000
ECM(-1)	-1.06215***	0.14201	-7.48	0.000
R-square	0.924			
Adj. R-square	0.895			

***p<1%

Table 7: Diagnostic test results

Test	HO	Stat.	p-value.
Breusch-Godfrey LM	No serial correlation	2.595	2.595
Glejser	Constant variance	1.334	1.334
Ramsey RESET	No omitted variables	0.183	0.183
Jarque-Bera	Normality	0.434	0.805

Table 8: OLS estimation results

Variable	Models				
	(1)	(2)	(3)	(4)	(5)
LnYN	1.2085***	16.8315***	29.5903***	12.2856***	8.3189***
	(0.0803)	(4.8002)	(2.2143)	(2.2401)	(2.5426)
LnYN2		-0.9970***	-1.9229***	-0.8005***	-0.5093***
		(0.3063)	(0.1460)	(0.1459)	(0.1735)
LnREN			-1.6359***	-0.7851***	-0.5316***
			(0.1363)	(0.1177)	(0.1448)
LnURB				1.1278***	0.8278***
				(0.1264)	(0.1629)
LnEIN					0.4075**
					(0.1575)
Constant	-3.5168***	-64.6352	-101.839***	-42.6185***	-29.1137***
	(0.6265)	(18.7847)	(8.2089)	(7.8304)	(8.8046)
R^2					0.9975
Adj. R^2					0.9970
B-G LM test					[0.8143]
Glejser test					[0.4831]
Ramsey test					[0.6762]
JB test					[0.1987]

Figure 4: CUSUM test results

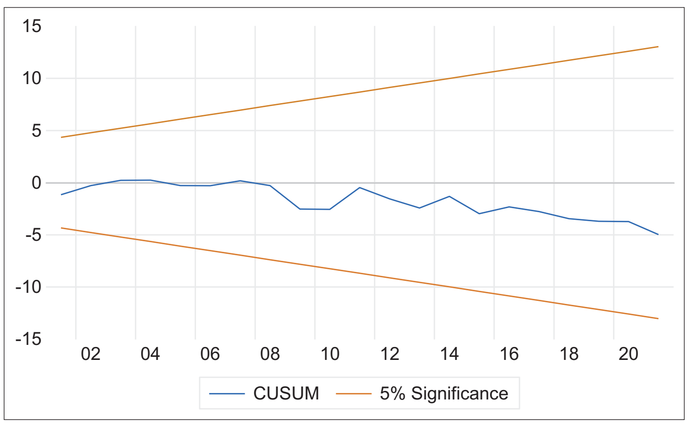
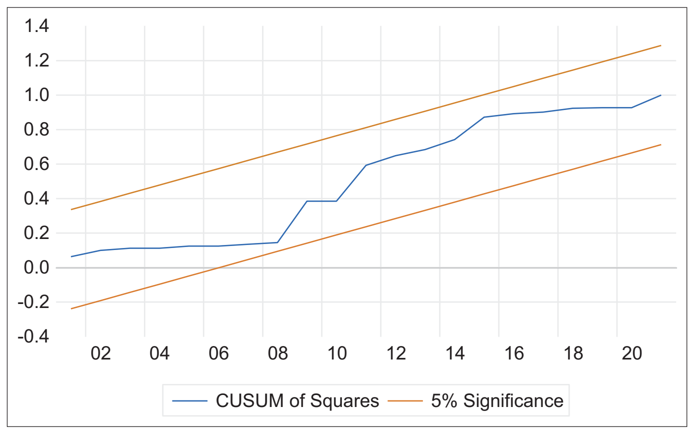


Figure 5: CUSUMSQ test results



and 5, the CUSUM and CUSUM of squares (CUSUMSQ) plots stay within critical values at 95% confidence bands during the observation. Thus, the stability of the estimated parameters is verified, indicating the absence of a structural break. It can be inferred that the ARDL (1,1,0,0,0,1) model is stable and reliable.

4.4. Robustness Check: OLS: Multistage Regression

To build confidence in the findings, this study includes a robustness test for the ARDL estimates. The robustness test is critical because the EKC model is sensitive to functional specification (Leal and Marques, 2022). Therefore, alternative estimation methods and model specifications are considered to prove whether the findings are consistent under different assumptions and model specifications.

Table 8 displays the results of multistage regressions (1 – 5 models) from OLS. The empirical results demonstrate that the EKC hypothesis is validated given that the results in Models 2-5 corroborate ARDL's estimates. LnYN is positively linked to CO_2 whereas $LnYN^2$ is negatively connected to CO_2. Other results demonstrate that urbanization and energy intensity have a positive impact on CO_2. Furthermore, renewable energy use has a negative influence on CO_2. Additionally, Gauss-Markov tests suggest that issues regarding serial correlation, heteroscedasticity, omitted variables, and random error terms are not verified. Lastly, in terms of the goodness of fit explanatory factors adequately account for the variability of CO_2 since the value of the Adj. r-square is exceptionally high (0.9970).

4.5. Causality Test

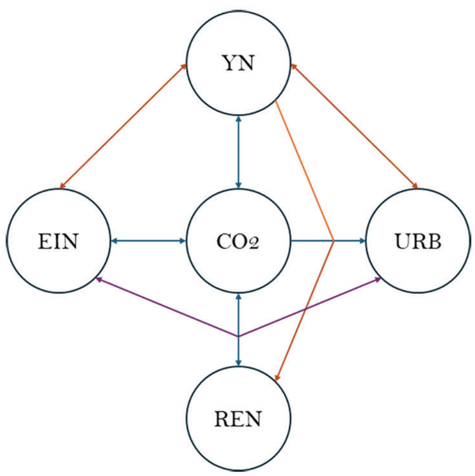
Regression such as ARDL-Bounds testing does not inherently prove a causal direction; therefore, this study incorporates cause-and-effect analysis using the TY Granger non-causality approach. As displayed in Table 9 and Figure 6, the results demonstrate that bidirectional causalities are predominant. There are feedback relationships between CO_2 and per capita GDP, CO_2 and urbanization, and CO_2 and renewable energy since the modified Wald statistics are statistically significant at a 1% critical value. The findings indicate that the past values of economic growth, urbanization, and renewable energy consumption significantly impact CO_2 emissions, and vice versa. These empirical findings align with previous studies (Dogan and Turkekul, 2016; Radoine et al., 2022; Espoir et al., 2023). Another result signifies a unidirectional causality from energy intensity toward CO_2 given

Table 9: TY causality test results

HO: (X granger causes Y)	χ^2	df	P-value
$LnCO_2$←LnGDP	34.931***	8	0.000
LnGDP←$LnCO_2$	232.940***	8	0.000
$LnCO_2$←LnURB	80.339***	8	0.000
LnURB←$LnCO_2$	249.350***	8	0.000
$LnCO_2$←LnREN	30.448***	8	0.000
LnREN←$LnCO_2$	189.860***	8	0.000
$LnCO_2$←LnEIN	18.012**	8	0.021
LnEIN←$LnCO_2$	149.110***	8	0.000
LnGDP←LnURB	4.667	4	0.323
LnURB←LnGDP	465.340***	4	0.000
LnGDP←LnREN	75.220***	8	0.000
LnREN←LnGDP	236.750***	8	0.000
LnGDP←LnEIN	30.696***	8	0.000
LnEIN←LnGDP	172.800***	8	0.000
LnURB←LnREN	59.298***	8	0.000
LnREN←LnURB	98.160***	8	0.000
LnURB←LnEIN	206.370***	8	0.000
LnEIN←LnURB	44.359***	8	0.000
LnREN←LnEIN	41.760***	8	0.000
LnEIN←LnREN	116.190***	8	0.000

*P<1%, **P<5%, ***P<1%

Figure 6: Graphical representation of causal directions



that the modified Wald statistics are statistically significant at a 5% critical value. This represents that the past value of energy intensity affects CO_2 whereas the past value of CO_2 does not cause energy intensity.

5. CONCLUSION

Discussing the drivers of environmental degradation is a critical issue for emerging economies such as Indonesia to provide policy coherence for sustainable development. This study examines whether the ECK hypothesis for CO_2 emissions is verified while concurrently unraveling the role of renewable energy consumption, energy intensity, and urbanization in the case of Indonesia using annual series from 1991 to 2021. Several econometrics methods are applied to provide reliable and robust findings such as ARDL-Bounds testing, the ZA test, OLS, and the TY causality test.

The empirical findings denote that the cointegration relationship between CO2, economic growth, urbanization, renewable energy, and energy intensity is firmly confirmed. The EKC hypothesis is validated with the predicted income turning point of 5,040.497 USD per capita, showing that the nexus between income and CO_2 follows the inverse U-shaped pattern. Despite the fact that improving energy efficiency is crucial, rapid urbanization is found to be more destructive to the environment compared to energy intensity. A 1% increase in the share of the urban population leads to a 0.74% scale-up in CO_2 whereas A 1% increase in energy intensity corresponds to a 0.49% boost in CO_2, ceteris paribus. The right side is that renewable energy use is confirmed to have a pivotal role in achieving sustainable development by lowering emissions since it is negatively associated with CO_2. The results from the TY test imply that bidirectional causalities are predominant among the observed variables. In accordance with the evidence, it is pivotal to promote energy efficiency while simultaneously enhancing the use of renewable energy generators in the effort to reduce CO_2 emissions in Indonesia.

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