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Testing the EKC Hypothesis in Indonesia: Empirical Evidence from the ARDL-Based Bounds and Wavelet Coherence Approaches

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Abstract

This study aims to explore the long-run and causal effects of energy consumption, trade openness and economic growth on CO_2 emissions in Indonesia. It employs newly developed econometric techniques using yearly data between 1980 and 2016. To capture long-run effects, the study uses the ARDL estimator, while the wavelet coherence technique is employed to investigate correlations and causal effects among the variables. The main novelty of the wavelet coherence technique is that it can obtain information on dynamic correlation and/or causality between economic variables at different frequencies and in different time periods. The findings from the ARDL long-run and short-run estimates reveal the validity of the environmental Kuznets curve (EKC) hypothesis in Indonesia. Furthermore, both economic growth and energy usage positively trigger CO_2 emissions, while trade openness enhances the environmental quality. The wavelet coherence approach also provides supportive evidence for the ARDL long-run estimate.

Keywords: CO_2 emissions, economic growth, energy consumption, Wavelet Coherence, Indonesia
JEL Classification: C32, F64, Q53, Q65

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1. Introduction

Among the most commonly discussed topics in academic literature and policy over the last few years is global warming, which is a symptom of climate change. The importance of the topic surfaced as a result of the increasing use of non-renewable resources for output resulting from industrialization and producing greenhouse gases (GHGs), which are the primary cause of global warming. Many intergovernmental and regional efforts have been made, including the Kyoto Protocol and the Paris Agreement. Advanced nations are required to limit their GHG emissions to under 5% of their 1990 levels, as agreed in the Kyoto Protocol, which is accompanied by the Paris Agreement in 2015, which seeks to constrain the universal average temperature increase by 2° C and to pursue efforts to limit the surge to 1.5 °C by second half of the 21st century (Kalmaz & Kirikkaleli, 2019).

Among many other GHGs in the atmosphere, CO_2 seems to have the maximum heat-absorbing capacity; hence, CO_2 emissions are considered to be the primary cause of climate change (Adebayo & Akinsola, 2021; Aytun, Akın, & Uçan, 2015; Mukhlis, 2020). Rapid economic growth creates improved living conditions, which can also be accomplished by an increment in production, the primary objective of emerging economies. However, the substantial rise in demand increases energy use, leading to high CO_2 emissions. In 2017, Indonesia was ranked 11th among the nations that emitted the most carbon dioxide (Energy Information Administration (EIA), 2020). The major sources of emissions in Indonesia include burning fossil fuels for energy, deforestation, and peatland mega-fires. Recently, Indonesia has been the world's largest exporter of thermal coal, a position that it took from Australia by accounting for almost 90% of Southeast Asia production (EIA, 2019).

In 2013, Indonesia contributed 4.47% of the global GHG emissions, which is 2161 million metric tons of CO_2 emissions equivalent (MtCO2e). Indonesia agreed, by unilateral measures, to reduce its greenhouse gas emissions in 2009 by 26% below the BAU point by 2020 and by 41% with international support. Indonesia adopted the national strategy for greenhouse gas emission reduction in 2011 through a Presidential Decree, which included 70 multisectoral initiatives to reduce GHG emissions to be implemented by local and central governments, civil society, and the private sector (Amheka & Higano, 2015). Indonesia pledged unquestioningly to lessen its GHG emissions by 26% by 2020 (following its pledge in 2009) and by 29% by 2030. In Indonesia, the CO_2 emissions per capita increased from 1.43 metric tons in 1999 to 2.09 metric tons in 2018, rising at a yearly average of 2.07%. The CO_2 emissions need to be lowered to under 551 MtCO2e by 2030 and under 128 MtCO2e by 2050 to be within its reasonable share spectrum consistent with the IPCC global 1.5 °C (Olhoff & Christensen, 2018).

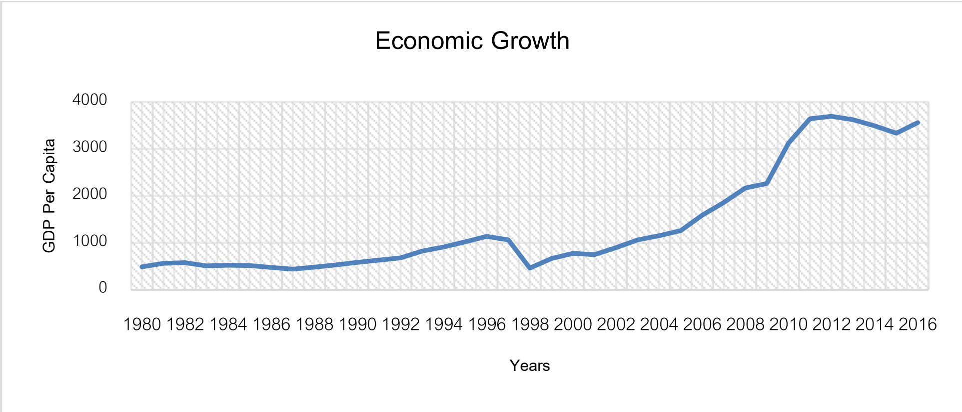

Figure 1: Economic growth

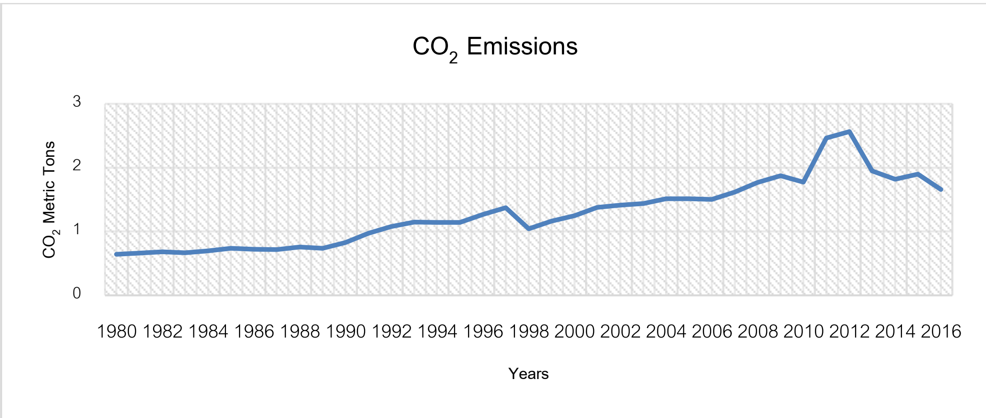

Figure 2: CO_2 emissions

In Southeast Asia, Indonesia is the biggest economy with a gross domestic product (GDP) amounting to $1.022 trillion, followed by Thailand ($409 billion), the Philippines ($369 billion), Malaysia ($349 billion), Singapore ($294 billion), Vietnam ($256 billion), Myanmar ($74 billion), Cambodia ($19 billion), Laos ($13.5 billion), Brunei ($9.6 billion), and Timor Leste ($2 billion), respectively, in 2018 (World Bank, 2020). On the global stage, Indonesia is ranked the 16th-largest economy behind Mexico. The Indonesian economy has shown tremendous progress over the last two decades. It was a victim of the Asian financial crisis in 1997; however, it has charted impressive growth ever since. As a developing nation, Indonesia has made significant progress in alleviating poverty, reducing the rate of poverty by 9.4% between 1999 and 2019. Indonesia's economic plan embraces a 20-year development plan between 2005 and 2025 (World Bank, 2020).

Indonesia surpassed India in 2012 as the fastest-growing economy in the G-20, with China taking the first spot. Since then, the growth rate has diminished, fluctuating around 5%. Indonesia raised its economic growth to slightly above 5% between 2016 and 2017 (World Bank, 2019). Nevertheless, the Government is still experiencing issues, including the weakening of the currency, declining exports, and slow consumer spending (Suprijanto, 2020). Indonesia ought to reorganize its domestic environmental policies, particularly those linked to the reduction of CO_2 emissions, highlighting the significance of this research. Therefore, the study incorporates the effect of energy consumption, trade openness, and economic growth on CO_2 emissions in Indonesia.

The issue of environmental pollutants is following a progressive trend in developing countries as they require more energy to achieve higher economic development. Consequently, they suffer from more environmental problems. Among the developing countries, Indonesia has been one of the fastest-growing open countries, showing rapid economic transformation, population expansion, and high energy consumption with a particular emphasis on the city context and a significant rise in pollutant emissions, specifically CO_2 emissions. Indonesia, which is an archipelagic state, is vulnerable to climate change. The choice of this country is also motivated by the fact that mixed findings have been generated in prior studies on the environmental Kuznets curve (EKC) hypothesis in Indonesia. For instance, Alam, Murad, Noman and Ozturk (2016), Guzel and Okumus (2020), Oktavilia and Firmansyah (2016), Sugiawan and Managi (2016), and Waluyo and Terawaki (2016) found support for the EKC hypothesis in Indonesia, while some studies have refuted the claim of the EKC hypothesis in Indonesia (Darwanto, Woyanti, Purbayu, Sasana and Ghozali 2019; Iskandar, 2019; Saboori and Soleymani, 2011).

Due to the inconclusiveness of the literature on Indonesia, this study intends to reexamine the EKC hypothesis in Indonesia by using the autoregressive distributed lag (ARDL) technique. Furthermore, the study uses the wavelet technique. The advantage of the wavelet coherence technique for this study is that it can gather information on dynamic linkages and causality simultaneously between CO_2 emissions and trade openness, energy usage, and economic growth in Indonesia at various frequencies and in different periods. Therefore, this study fills this gap in the existing literature. The next segment contains a synopsis of the related studies. The third segment discusses the data and methods utilized. The fourth segment presents the findings based on the methods adopted. The fifth segment discusses the conclusion and policy directions.

2. Conceptual framework

Over the past few decades, numerous studies in energy economics have examined the validity of the environmental Kuznets curve (EKC) hypothesis, considering the growing attention paid to environmental concerns. The EKC hypothesis postulates an inverted-U-shaped relationship between different pollutants and per capita income; that is, environmental pressure increases up to a certain level as income rises and afterwards it decreases. There are four key trends in the research focusing on this issue.

Grossman and Krueger (1995) made the first attempts to check whether the EKC hypothesis is true by examining the effect of real output on CO_2 emissions (De Freitas & Kaneko, 2011; Pata, 2018; Zhang, Liu, Wang, & Zhou, 2013). According to the EKC theory, an inverted U-shape is depicted in the interaction between real growth and CO_2 emissions. It demonstrates a surge in environmental degradation as the real output increases in the early stages of economic growth and a decline in pollution as economic growth increases after reaching a threshold due to enhancements in technology, eco-friendly regulations at the domestic and international levels, and enhanced awareness among the public, causing a reduction in environmental pollution (Kirikkaleli & Kalmaz, 2020; Kurniawan & Managi, 2018; Mahmood, Maalel, & Zarrad, 2019; Mensah et al., 2019). Adu and Denkyirah (2018) examined the EKC hypothesis in selected West African countries with similar income statuses using a panel dataset from 1970 to 2013. The empirical finding revealed that economic growth in the short run significantly increases CO_2 emissions but does not significantly decrease CO_2 emissions. The non-significant relationship between economic growth and environmental pollution indicates the non-existence of the EKC in West Africa.

The second aspect intends to explore the effect of real growth and energy use on CO_2 emissions by implementing causality and cointegration tests after Kraft and Kraft's (1978) research. Energy usage is perceived to be the key force triggering pollution via fossil fuel burning (Narayan & Smyth, 2008; Yuan, Kang, Zhao, & Hu, 2008). Utilizing data stretching from 1972 to 2013, Vo and Le (2019) explored the linkages between energy usage, CO_2 emissions, and economic growth. The authors found that, in Bangladesh and Egypt, economic growth triggers CO_2 emissions. In the Philippines, Turkey, and Vietnam, causality was observed from economic growth to energy usage.

Salman, Long, Dauda, and Mensah (2019) researched the influence that energy usage and real output have on the environmental degradation in Indonesia, South Korea, and Thailand by deploying FMOLS, DOLS, and panel Granger causality. The findings revealed that energy consumption and economic growth have a positive interconnection with environmental degradation in Indonesia, South Korea, and Thailand.

Pao and Tsai (2010), in their study on the interactions among energy consumption, economic growth, and CO_2 emissions in BRIC economies, observed that environmental degradation is affected positively by energy use and economic growth. Omri (2013) examined the interconnection between energy utilization, economic growth, and environmental degradation in 14 MENA economies. The empirical findings revealed feedback causal linkages between energy consumption and economic growth, while unidirectional causality exists from energy usage to CO_2 emissions. Esso and Keho (2016), using time series data between 1971 and 2010, investigated the linkages between energy usage, CO_2 emissions, and economic growth in 12 selected Sub-Saharan African nations. The investigators found inconsistent results across nations, though; energy consumption and GDP growth were connected with an upsurge in environmental degradation in most nations.

Odugbesan and Rjoub (2020) used the economies of Mexico, Indonesia, Nigeria, and Turkey (MINT) as a case study to investigate the influence of energy usage, urbanization, and real growth on environmental pollution. Their findings revealed that the energy–growth hypothesis holds for the MINT economies, whereas they found long-run causality running from economic growth, energy usage, and CO_2 emissions to urbanization. Likewise, Adebayo, Awosusi, and Adeshola (2020) re-examined the CO_2 emission determinants in the MINT nations utilizing panel data. The investigators found a positive correlation between CO_2 emissions and energy usage, though no significant interaction was found between CO_2 and economic growth.

The third strand of the literature has included trade openness in the model to examine the interaction between energy consumption, environmental degradation, economic growth, and trade openness (Adebayo et al., 2020; Bernard & Mandal, 2016; Kirikkaleli & Kalmaz, 2020). For instance, Ajayi and Ogunrinola (2020) and Bernard and Mandal (2016) found that trade openness is a key determinant of carbon emissions in the long run. In contrast, in the studies by Naranpanawa (2011) and Salman et al. (2019), the relationship between trade openness and CO_2 emissions was insignificant. The finding obtained in the study by Sharma (2011) on the determinants of environmental pollution showed a positive link between trade openness and environmental pollution in 69 countries. Several studies conducted in Indonesia (Oktavilia & Firmansyah, 2016; Waluyo & Terawaki, 2016) have found a positive link between CO_2 emissions and economic growth.

The fourth strand emerged recently due to the inconclusiveness of the results obtained in the previous literature as a result of different countries being in focus, the methodology employed, and the time frame. Thus, some researchers used time domain frequency analysis to explore the linkages between environmental degradation and its determinants. For example, Mutascu and Sokic (2020) used wavelet tools to examine the trade openness–CO_2 emissions linkage in EU nations. The findings revealed that, in the short term and the long term, CO_2 emissions drive trade openness. Using the wavelet coherence–based causality technique, Kalmaz and Kirikkaleli (2019) investigated the link between CO_2 and its determinants in Turkey between 1960 and 2015. The investigators found a positive correlation between CO_2 emissions and trade openness, energy usage, and economic growth. Khochiani and Nademi (2019) examined the link between CO_2 emissions, energy consumption, and economic growth in the United States, China, and India. The findings obtained from this study demonstrated a positive correlation between economic growth and CO_2 emissions in the USA and China.

The findings obtained by Kalmaz and Kirikkaleli (2019) demonstrated that economic growth and energy consumption exert a positive impact on CO_2 emissions. Bilgili et al. (2020) examined the co-movement of renewable energy usage and CO_2 emissions in the United States between 1980Q1 and 2018Q12. Their findings indicated that renewable energy was effective in reducing CO_2 emissions after the second half of 2010.

It is clear from the studies examined that the association between economic growth, CO_2 emissions, and energy usage has been extensively explored. Nonetheless, research using the wavelet coherence technique to verify the effect of economic growth, trade openness, and energy usage on CO_2 emissions is scant. Therefore, this study fills the gap in the existing literature.

3. Data and methodology

The dataset utilized in this study was gathered from the World Bank database stretching between 1980 and 2016. The CO_2 emissions (CO_2), which are the dependent variable, are measured in metric tons per capita, and trade openness (TR) is measured as a share of the total trade percentage of the GDP. Furthermore, energy usage is calculated as kt of oil equivalent per capita, economic growth is calculated as GDP per capita constant 2010 US$, and economic growth squared (GDP^2) is calculated as the square of the GDP per capita constant 2010 US$. The natural log of all the series is taken to conform to normality (Awosusi, Adebayo, & Ajayi, 2020; Eminer, Awosusi, & Adebayo, 2020; Onyibor, Bah, & Tomiwa, 2018). The motive of this study is to re-examine the traditional EKC hypothesis. The research also explores the effect of real growth, trade, and energy use on CO_2 emissions by using the ARDL and wavelet coherence techniques.

In order to achieve the study objectives, the study utilize the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root tests and the more recent Zivot–Andrews (ZA) unit root test to obtain the integration order of series. As a further phase in this analysis, the investigator utilizes the ARDL bound test to examine the cointegration in the long run between CO_2 and other explanatory variables in Indonesia. The benefit of the ARDL method is the capability to examine both short- and long-run interconnection together when series are I(0) or I(1) or both I(0) and I(1), respectively, though it will not work for I(2) series. The framework for the ARDL model is constructed in Equation 1 as follows;

$$\Delta CO_{2t} = \vartheta_0 + \sum_{i=1}^{t} \vartheta_1 \Delta CO_{2t-i} + \sum_{i=1}^{t} \vartheta_2 \Delta ENE_{t-i} + \sum_{i=1}^{t} \vartheta_3 GDP_{t-1}^2 + \sum_{i=1}^{t} \vartheta_4 GDP_{t-i} + \sum_{i=1}^{t} \vartheta_5 \Delta TR_{t-i} + \varepsilon_t \qquad [1]$$

where Δ represents the first difference. The variables' coefficients in the long run are illustrated by ϑ_1......5. After long-run connections have been determined, short-run interconnections are examined using the error correction model (ECM) developed by Engle and Granger (1987) to analyze the short-run coefficients and the error correction term (ECT). This is achieved by adding the ECM to the ARDL framework as follows:

$$\Delta CO_{2t} = \vartheta_0 + \sum_{i=1}^{t} \vartheta_1 \Delta CO_{2t-i} + \sum_{i=1}^{t} \vartheta_2 \Delta ENE_{t-i} + \sum_{i=1}^{t} \vartheta_3 GDP_{t-1}^2 + \sum_{i=1}^{t} \vartheta_3 GDP_{t-i} + \sum_{i=1}^{t} \vartheta_4 \Delta TR_{t-i} + ECT_{t-i} + \varepsilon_{t-1} \qquad [2]$$

where φ illustrates the speed of adjustment and the error term is shown by ECT_{t-1}, which signifies the error correction term.

With respect to the main aim of this study, the investigator explores the time–frequency dependence between CO_2 emissions, economic growth, trade openness, and energy consumption in Indonesia by employing the wavelet coherence approach. The main novelty of wavelet coherence is that it can obtain information on dynamic correlation and/or causality between economic variables at different frequencies and in different time periods. Therefore, it allows the present study to capture the long- and short-run correlations and causal links between CO_2 emissions, trade openness, and energy consumption in Indonesia. It is well known that, if there is a structural break(s) in the time series, traditional causality tests usually generate inaccurate findings. Consequently, this study utilizes the wavelet coherence approach to avoid this issue. The main advantage of wavelet coherence is that the decomposition of one-dimensional time data into the bi-dimensional time–frequency sphere is allowed. Thus, it is possible to capture the long-run and short-run causal interactions between CO_2 emissions, trade openness, economic growth, and energy consumption in Indonesia at the same time.

A multi-scale decomposition technique produces a natural framework to show the frequency dependence behavior for examining the interconnection between CO_2 emissions, economic growth, and energy consumption (Kirikkaleli & Gokmenoglu, 2020). This research offers the opportunity to reveal the long-term, medium-term, and short-term causal associations among CO_2 emissions, economic growth, and energy consumption. Goupillaud, Grossmann, and Morlet (1984) first presented the methods. The present study utilizes the ϖ wavelet method, which is part of the Morlet wavelet family. The equation of a wavelet ϖ, which is part of the Morlet wavelet family, is as follows:

$$\varpi(t) = \pi^{-\frac{1}{4}} e^{-i\varpi t} e^{-\frac{1}{2}t^2} \qquad [3]$$

The frequency used is illustrated by w based on the restricted time series; i demonstrates p (t), n = 0, 1, 2, 3…N-1; and $\sqrt{-1}$. According to Adebayo and Beton Kalmaz (2020) and Kirikkaleli (2020), there is a time transformation to the time–frequency domain that correlates with the wavelet. ϖ is changed; therefore, it is transformed into $\varpi_{k,f}$, as demonstrated in Equation 4:

$$\varpi_{k,f}(t) = \frac{1}{\sqrt{h}} \varpi\left(\frac{t-k}{f}\right), \quad k, f \in \mathbb{R}, f \neq 0 \qquad [4]$$

The time series p(t) is incorporated. Hence, the continuous wavelet function is illustrated by Equation 5:

$$\varpi_p(k,f) = \int_{-\infty}^{\infty} p(t) \frac{1}{\sqrt{f}} \overline{\varpi\left(\frac{t-k}{f}\right)} dt \qquad [5]$$

According to Adebayo and Akinsola (2021) and Alola and Kirikkaleli (2019), when ψ, which is the coefficient, is integrated into the equation, Equations 6 and 7 are reinstated.

$$p(t) = \frac{1}{C_{\varpi}} \int_{0}^{\infty} \left[\int_{-\infty}^{\infty} \left| \mathfrak{w}_p(a,b) \right|^2 da \right] \frac{db}{b^2} \qquad [6]$$

Equation 7 is used to capture the vulnerability of energy usage, CO_2 emissions, economic growth, and trade openness. The wavelet power spectrum (WPS) is as follows:

$$WPS_p(k,f) \left| W_p(k,f) \right|^2 \qquad [7]$$

The cross-wavelet transformation (CWT) process transforms the time series in Equation 7 into Equation 8.

$$W_{pq}(k,f) = W_p(k,f)\overline{W_q(k,f)} \qquad [8]$$

Where Wp(k,f) and Wq(k,f) stand for the two time series and the squared wavelet coherence is represented in Equation 9:

$$R^2(k,f) = \frac{\left| S\left(f^{-1} W_{pq}(k,f)\right) \right|^2}{S\left(f^{-1} \left| W_p(k,f) \right|^2\right) S\left(f^{-1} \left| W_q(k,f) \right|^2\right)} \qquad [9]$$

If the $R^2(k,f)$ nears 1, it indicates that either the time series indicators are correlated or there is a causal interaction between the time series indicators at a particular level, enclosed by a black line. Additionally, whenever $R^2(k,f)$ nears 0, it indicates that there is no proof of association or causality between the two variables. However, $R^2(k,f)$ cannot provide any detailed information on the correlation symbol. Hence, Torrence and Compo (1998) developed a method for identifying distinctions in wavelet coherence by using deferral signs in the wavering of two time sequences. Equation 10 is the equation for the developed wavelet coherence:

$$\phi_{pq}(k,f) = \tan^{-1} \left(\frac{L\left\{ S\left(f^{-1} W_{pj}(k,f) \right) \right\}}{O\left\{ S\left(f^{-1} W_{pj}(k,f) \right) \right\}} \right) \qquad [10]$$

An imaginary operator and a real part operator are symbolized by *L* and *O* separately.

4. Empirical findings

Due to the inconclusiveness of earlier studies, the current study examines the influence of energy use, trade openness, economic growth squared, and economic growth on CO_2 emissions in Indonesia. The investigator used the ARDL and wavelet coherence techniques to address this void in the earlier studies and to answer the question "How do energy usage, economic growth, and trade influence CO_2 emissions in Indonesia?" Table 1 presents the variables' descriptive statistics. The findings from Table 1 show that CO_2 emissions, energy consumption, and economic growth squared have a normal distribution while economic growth and trade openness do not show normal distribution, as revealed by the skewness. Furthermore, as indicated by the kurtosis, all the variables demonstrate normal distribution with the exception of trade openness. The Jarque–Bera p-value reveals that CO_2 emissions and energy consumption are normally distributed while economic growth squared, economic growth, and trade openness are not normally distributed.

Table 1: Descriptive statistics

	CO_2	ENE	GDP	GDP^2	TR
Mean	1.284	655.36	1388.72	564344	53.916
Median	1.245	688.37	900.17	480299	52.654
Maximum	2.564	883.91	3694.34	13645636	96.186
Minimum	0.642	377.74	442.21	195364	37.421
Std Dev.	0.508	175.93	1127.5	357685	10.148
Skewness	0.598	-0.3531	1.1388	0.7951	2.0373
Kurtosis	2.794	1.669	2.7152	2.5124	9.4622
Jarque–Bera	2.275	3.4986	8.1234	4.26499	89.977
Probability	0.320	0.1739	0.0172	0.11854	0.0000
Observations	37	35	37	37	37

The integration order of the time series is investigated as a preliminary test, utilizing the two standard root unit tests (ADF and PP) as well as the KPSS. Furthermore, to ascertain whether there are any structural breaks in the series, the Zivot–Andrews (ZA) unit root test is performed. The results obtained from the unit root tests at intercept and trend are presented in Table 2. The results obtained from the ADF, PP, and KPSS tests indicate that the variables are integrated at mixed order, that is, I(0) and I(1).

Table 2: Unit root tests

Panel T: Conventional Unit Roots								
Tests	CO_2	Order	ENE	Order	GDP	Order	TR	Order
ADF	-3.38***	I(0)	-6.15*	I(1)	-5.93*	I(1)	-8.24*	I(1)
PP	-12.28*	I(1)	-6.20*	I(1)	-5.93*	I(1)	-8.73*	I(1)
KPSS	0.14***	I(0)	0.17**	I(0)	0.15**	I(0)	0.19**	I(0)
Panel A: Unit Root with a Structural Break								
ZA	-5.19**	I(0)	-5.94*	I(1)	-6.19*	I(1)	-7.00*	I(0)
	[1991]		[1990]		[2002]		[1998]	

*, **, and *** stand for the significance levels of 1%, 5%, and 10%, correspondingly.

Since the variables are stationary at a mixed level in Table 2, the ARDL bounds testing proposed by Pesaran, Shin, and Smith (2001) is utilized to examine the cointegration. Table 3 presents the outcome of the cointegration test. The findings reveal that there is evidence of cointegration in the model since the F-statistic (5.85) is greater than the lower bound and upper bound critical values. Based on this finding, the null hypothesis is rejected in the model at the 1% significance level. This finding paves the way for investigating the long-run and short-run ARDL.

Table 3: ARDL bounds test

Model Estimated		
CO_2=f(ENE, GDP GDP^2, TR)	(1,4,4,3,4)	
F-statistic	5.85*	
Cointegration	Yes	
Significance Level	L-B I(0)	U-B I(1)
1%	3.74	5.06
5%	2.86	4.01
10%	2.45	3.52

Note: * and ** portray the 1% and 5% significance levels, correspondingly. L-B and U-B indicate the lower and upper bounds, correspondingly.

Long-Run and Short-Run Estimation Findings

After establishing cointegration between CO_2 and the independent variables, the study investigates the short- and long-run connections between CO_2 emissions and their determinants. The output of the short- and long-run interconnection is presented in Table 4. The ARDL reveals the following results. (i) The EKC hypothesis is valid for Indonesia in the long and the short run with the GDP^2 having a detrimental effect on CO_2 emissions. This finding concurs with the findings of De Freitas and Kaneko (2011), Kirikkaleli and Kalmaz (2020), and Zhang et al. (2013). (ii) There is a positive and significant interconnection between energy usage and CO_2 emissions. This outcome corroborates past studies (Adebayo et al., 2020; Kalmaz & Kirikkaleli, 2019; Kurniawan & Managi, 2018; Salman et al., 2019). (iii) Trade openness has a detrimental impact on CO_2 emissions in Indonesia. This implies that the trade policy in Indonesia enhances the environmental quality. This result corresponds to the findings obtained by Kalmaz and Kirikkaleli (2019) and Mutascu and Sokic (2020). (iv) Economic growth has a positive impact on CO_2 emissions. This indicates that growth in the economy is causing an adverse effect on the environmental quality. This result corroborates the findings of Esso and Keho (2016), Kalmaz and Kirikkaleli (2019), Omri (2013), Pao and Tsai (2010), and Vo and Le (2019). As anticipated, the ECM's coefficient is -0.45, which is negative and statistically significant at the 1% level of significance. This illustrates that past periods can be corrected by subsequent periods in the model. Additionally, numerous diagnostic tests are performed on the model. Premised on the tests conducted, the model has a good fit and does not suffer from any misspecification. The results of the CUSUM and CUSUMsq in Figures 3a and 3b illustrate that the model is stable at the significance level of 5%.

Table 4: ARDL long-run and short-run estimations

	Long-Run Result			Short-Run Result		
	Reg	Coeff	T-stat	Reg	Coeff	T-stat
CO_2	ENE	0.60	2.73**	ENE	1.62	4.62*
	GDP	0.59	3.33*	GDP	0.59	5.07*
	GDP^2	-0.80	-1.93***	GDP^2	-0.43	2.13***
	TR	-0.44	-2.39**	TR	-0.48	-2.24**
				ECM(-)	-0.45	-4.62*
Diagnostic Tests						
	R^2				0.98	

Adj. R^2	0.97
χ^2 Heteroscedasticity	0.52(0.89)
χ^2 Ramsey	0.63(0.41)
χ^2 Normality	1.12(0.57)
χ^2 LM	1.33(0.30)

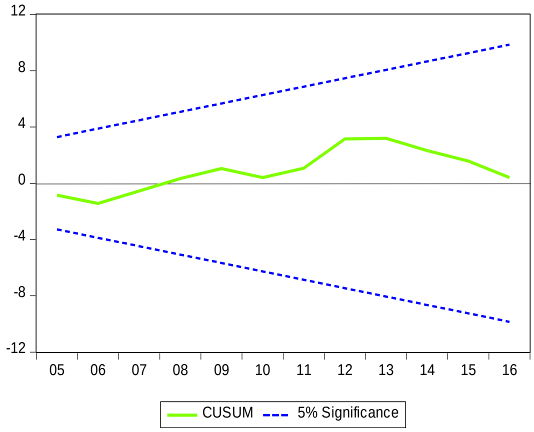

Figure 3a: CUSUM

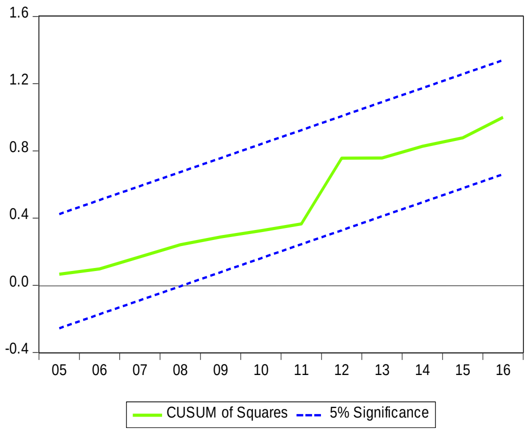

Figure 3b: CUSUM squares

Wavelet Coherence Findings

When analyzing wavelet coherence (WTC), the white cone is the cone of influence (COI) that will be used for interpretation. The significance level is indicated by the thick black line determined based on the Monte Carlo simulations. In addition, in Figures 4, 5, and 6, periods 0–8, 8–16, and 16 and above represent the short term, medium term, and long term, respectively. In accordance with Adebayo (2020), Adebayo and Beton Kalmaz (2020), Kalmaz and Kirikkaleli (2019), and Pal and Mitra (2017), the time is displayed on the horizontal axis while the vertical axis shows the frequency (the lower the frequency, the higher the scale). Regions in time–frequency space where the two time series co-vary are located by the wavelet coherence. Warmer colors (red) represent regions with significant interrelation, while colder colors (blue) signify lower dependence between the series.

Cold regions beyond the significant areas represent time and frequencies with no dependence in the series. An arrow in the wavelet coherence plots represents the lead/lag phase relations between the examined series. A zero-phase difference means that the two time series move together on a particular scale. Arrows point to the right (left) when the time series are in phase (anti-phase). When the two series are in phase, it indicates that they move in the same direction, and anti-phase means that they move in the opposite direction. Arrows pointing to the bottom right or top left indicate that the first variable is leading, while arrows pointing to the top right or bottom left show that the second variable is leading.

Figures 4, 5, and 6 illustrate the wavelet coherence between CO_2 and the independent variables between 1980 and 2016. This technique captures the correlation and causality between CO_2 and the predictors simultaneously. This technique was developed from econophysics, and it fuses information concerning the time and frequency domains. As stated by Gokmenoglu, Kirikkaleli, and Eren (2019) and Kirikkaleli (2020), this approach was derived from mathematics by integrating the time and frequency domain information methods to collect previously unknown information. Hence, it enables the current research to investigate the correlation and causality in the short and long run between the dependent variable (CO_2 emissions) and the regressors (economic growth, trade, and energy usage) in Indonesia. In Figures 4, 5, and 6, no correlation between the two variables is depicted by a cold (blue) color while evidence of correlation is portrayed by a warmer (red) color.

The arrows surrounding the thick black line in the wavelet coherence figure show the path of causality and correlation. In Figure 4, between 1982 and 1990, there is evidence of rightward arrows at dissimilar scales, which depict a positive correlation between CO_2 and energy usage. The rightward and downward arrows show that CO_2 emissions cause energy usage. In the long term between 1992 and 2005, the rightward arrows denote a positive correlation between CO_2 and energy use. The rightward and upward arrows signify that energy usage leads CO_2 emissions during this period. In Figure 5, there is proof of rightward arrows in the short term and medium term, indicating a positive correlation between CO_2 and economic growth. Additionally, the rightward and upward arrows indicate that economic growth leads CO_2 emissions. Furthermore, between 1994 and 2003, at different scales, there is evidence of a positive correlation between CO_2 emissions and economic growth, as illustrated by the rightward arrows. In addition, the rightward and upward–downward arrows indicate that CO_2 causes economic growth. No evidence of correction is found between CO_2 emissions and energy consumption between 2003 and 2010. In Figure 6, at different scales, there is no significant correlation between CO_2 emissions and trade openness. However, between 1993 and 2004, in the short and medium terms, there is proof of a negative correlation between CO_2 emissions and trade openness in Indonesia. The leftward and upward arrows during this period signify that trade openness causes $C0_2$ emissions.

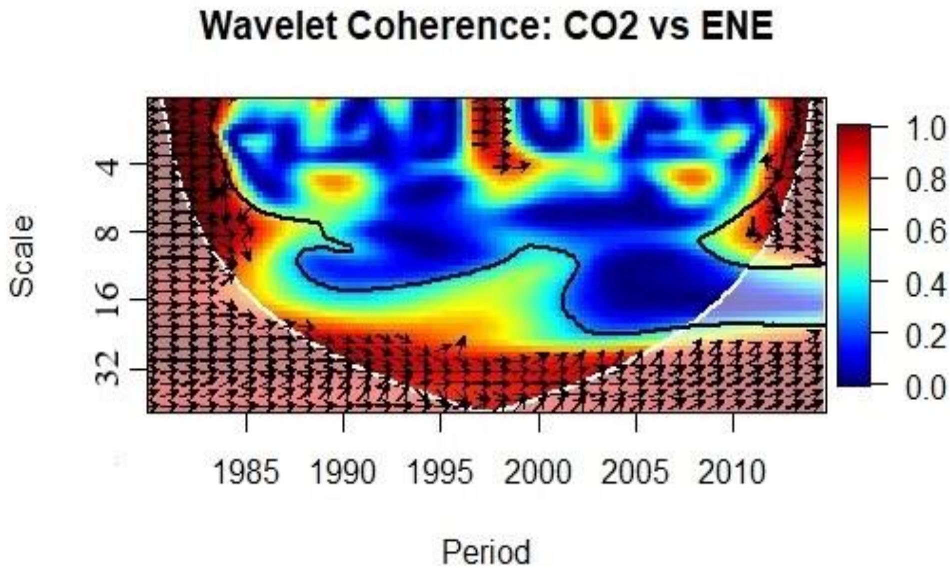

Figure 4: WTC between CO_2 and ENE

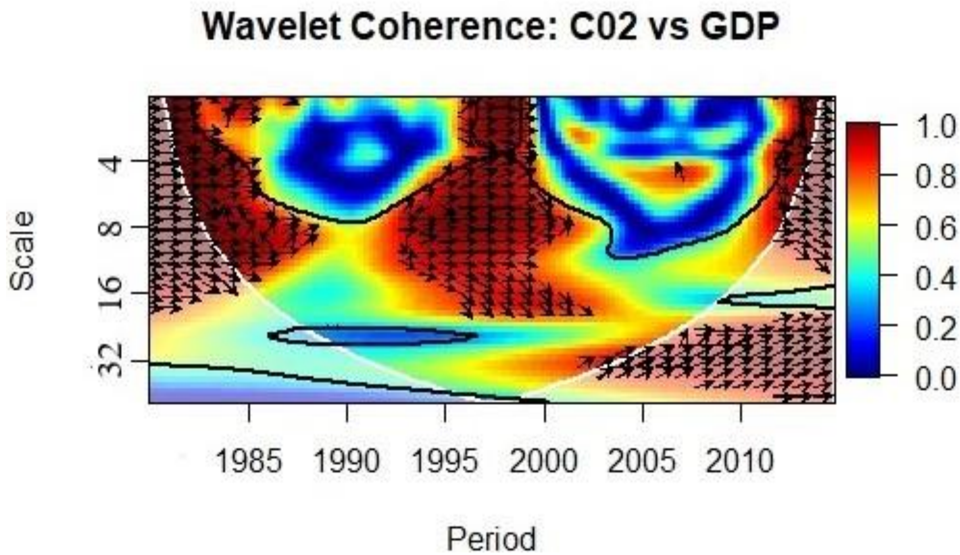

Figure 5: WTC between CO_2 and GDP

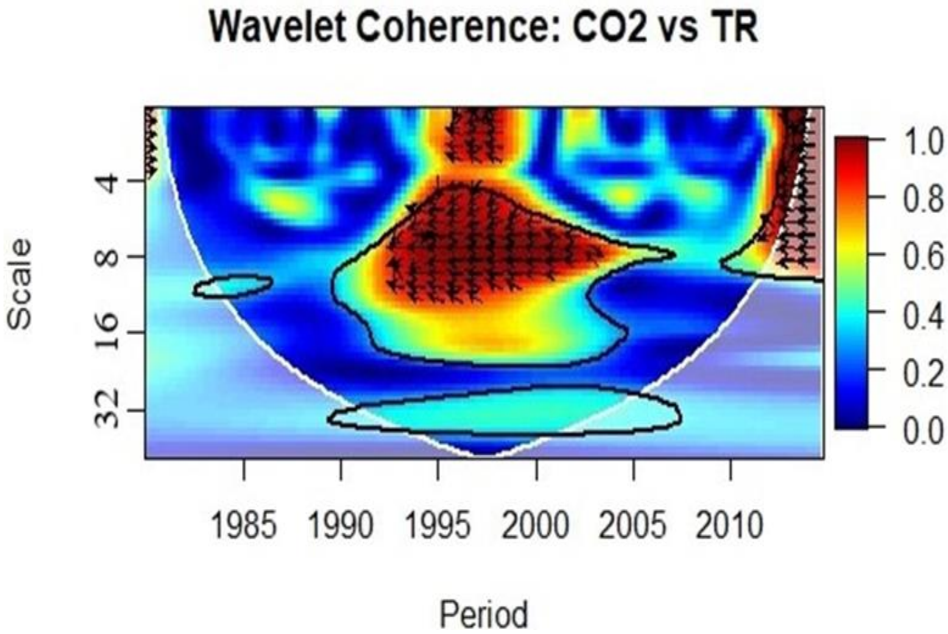

Figure 6: WTC between CO_2 and TR

5. Conclusion and policy implications

By researching the long-run and causal impact of economic growth, trade openness, and energy consumption on Indonesia's CO_2 emissions by utilizing the ARDL and wavelet coherence techniques, this research intends to give fresh knowledge to the CO_2 literature. To the researchers' knowledge, no prior studies have specifically explored the short-, medium-, and long-run causal impacts of economic growth, trade openness, and energy use on CO_2 emissions in Indonesia with the wavelet approach. The key novelty of the wavelet coherence technique is that it can differentiate between various interactions that emerge at the same time but at different frequencies. Furthermore, it is suitable for identifying structural break(s) and transient stationary and non-stationary linkages. To explore these linkages, this study utilizes yearly data spanning the period 1980 to 2016. The findings reveal the following: (i) the validity of the EKC hypothesis in Indonesia; (ii) positive and significant interaction between energy usage and CO_2 emissions; (iii) detrimental interaction between trade openness and CO_2 emissions; and (iv) positive interaction between real growth and CO_2. The result obtained from the wavelet coherence technique reveals that both economic growth and energy usage have a position relationship with CO_2 emissions while the relationship between trade openness and CO_2 emissions is negative. The finding from the wavelet coherence technique further supports the ARDL techniques.

In this regard, the government can help the markets by establishing a strong policy framework that creates long-term value for greenhouse gas emission reductions and consistently supports the development of new technologies that lead to a less carbon-intensive economy. Another interesting observation regarding our finding is that policies directed to trade openness and liberalization to attract higher levels of R & D related foreign direct investment can decrease the environmental degradation as our evidence shows that trade openness reduces environmental degradation. This is important because a higher degree of economic and financial openness strengthens the institutional framework, creating incentives for firms to act. Therefore, addressing these issues might lead to higher energy efficiencies through technological advances and reduce the CO_2 emissions in Indonesia.

Furthermore, the implementation of a carbon tax should be initiated by the decision makers on polluters to prevent ecological pollution at the minimum for the short-term regulation of CO_2 emissions. Additionally, Indonesia should initiate stronger policies toward enhancing the efficiency of energy and energy usage programs to minimize unnecessary energy waste. These would enhance energy security and ensure a reduction in carbon emissions without having a detrimental effect on economic growth. Though the current research examines substantial empirical results for Indonesia's scenario, one of the critical drawbacks of our analysis is the accessibility of the data, limiting the power of the econometric techniques used because the accessible variables only encompass the period between 1980 and 2016.

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