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- About
- Aims and Scope
- Editorial Board
- Instructions for Authors
- Article Processing Charge
- Publication Ethics
- Submission
- Current Issue
- Archive
- Citation List

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Aligning Energy and Macroeconomic Policies Toward Carbon Dioxide Emissions Reduction for Sustainable Development Planning: An Error Correction Model Approach

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Abstract:

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CO_2 emissions, sustainable development, Error Correction Model, renewable energy, climate policy

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Aligning Energy and Macroeconomic Policies Toward Carbon Dioxide Emissions Reduction for Sustainable Development Planning: An Error Correction Model Approach

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ABSTRACT

Aligning economic and energy policies to mitigate climate change is a crucial challenge for global sustainable development planning. This study aims to analyze the short-term and long-term dynamic impacts of renewable energy consumption, economic growth, trade openness, and Foreign Direct Investment (FDI) on CO_2 emissions in Indonesia from 2000 to 2023. Using the Error Correction Model (ECM) approach, this study presents new empirical evidence regarding the dynamics of adjustment in the relationship between the economy, energy, and environment in Indonesia. The results of long-term estimates show that renewable energy consumption is a significant factor in mitigating CO_2 emissions. Conversely, economic growth and FDI were found to increase emissions, which provides support for the pollution haven hypothesis in the case of Indonesia. In the short term, renewable energy and trade openness contribute to reductions in emissions. A key finding of this study is the existence of a very fast and overshooting error correction mechanism, which indicates that any disequilibrium that occurs can be corrected entirely within a year. Policy recommendations focus on accelerating the transition to renewable energy to achieve sustainable green growth.

1. INTRODUCTION

The imperative for climate change mitigation, as enshrined in the Sustainable Development Goal of Climate Action, has put carbon dioxide (CO_2) emissions at the forefront of the global policy agenda. Increasing greenhouse gas concentrations pose a significant threat to environmental sustainability and socio-economic stability, thus demanding a paradigm shift in development planning [1, 2]. As the country with the largest economy in Southeast Asia and significant natural capital, Indonesia occupies a central position in this global effort. Indonesia's commitment to achieve Net Zero Emissions by 2060, with a temporary emission reduction target of 29% (unconditional) to 41% (conditional) by 2030, requires a deep understanding of the complex interplay between energy policy, macroeconomic dynamics, and environmental impacts [3-5].

Academic discourse on the determinants of CO_2 emissions is extensive, with a focus largely centred on the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverse U-shaped relationship between economic growth and environmental degradation [6]. A substantial body of literature has explored this relationship, examining the roles of energy consumption, trade, and investment. For example, various studies consistently confirm that the transition to renewable energy sources—such as solar, hydro, and geothermal—is fundamental to decoupling economic growth from emissions [5, 7]. At the same time, the impact of macroeconomic variables such as trade openness and Foreign Direct Investment (FDI) presents a more nuanced picture. While some experts argue that trade and FDI can facilitate cleaner technology transfer, "the halo effect", others warn that developing countries may become "pollution havens" by attracting carbon-intensive industries [1, 8, 9].

Although a considerable amount of research exists, critical gaps remain in the literature, particularly in the Indonesian context. Most previous studies have employed static methods, which often fail to capture the complex and time-sensitive dynamics inherent in macroeconomic systems. These studies tend to focus on long-term relationships without adequately distinguishing them from short-term adjustment pathways. As a result, a crucial question remains unanswered: When there are policy shocks—such as new investments in renewable energy or changes in trade policy—how do CO_2 emissions and related economic variables react in the short term, and how quickly do they reintegrate into their long-term equilibrium? This temporal dimension is critical for policymakers who must navigate urgent economic pressures while steering countries toward long-term sustainability goals. The absence of a model that simultaneously analyzes long-term equilibrium, short-term dynamics, and adjustment velocity is a significant gap that this study aims to fill.

This paper introduces a significant methodological novelty to address this gap by using a dynamic Error Correction Model (ECM). The ECM framework is uniquely suited for this analysis because it allows differentiation between short-term effects and long-term equilibrium relationships [10]. By integrating the term error correction, it not only estimates the impact of renewable energy consumption, economic growth, trade openness, and FDI on CO_2 emissions but, more importantly, measures the speed at which the system adjusts to correct short-term deviations and restore its long-term balance. This approach provides a more robust and policy-relevant understanding than conventional static models, while also offering insights into the resilience and responsiveness of economic, energy, and environmental relationships.

Therefore, the primary objective of this study is to analyse the short-term and long-term effects of renewable energy consumption, economic growth, trade openness, and FDI on CO_2 emissions in Indonesia for the period 2000-2023 using a dynamic ECM. Thus, this study aims to provide empirical evidence to inform the alignment of energy and macroeconomic policies, ensuring that these two policies reinforce each other in achieving sustainable development and the country's climate commitments. The findings of this study aim to provide policymakers with actionable insights for designing effective and sustainable interventions in both the short and long term.

The rest of this paper is arranged as follows. Section 2 presents a detailed review of the relevant literature. Section 3 outlines the data sources and specifications of the ECM. Section 4 presents and discusses empirical results, including diagnostic tests and robustness tests. Finally, Section 5 closes the paper with key policy implications and suggestions for future research.

2. LITERATURE REVIEW

This section reviews theoretical frameworks and relevant previous empirical studies on the determinants of CO_2 emissions. The primary theoretical foundation used to analyze the relationship between economic development and environmental quality is the EKC hypothesis. First introduced by Grossman and Krueger, this hypothesis posits that in the early stages of economic development, environmental degradation tends to increase in tandem with growth in per capita income [6, 11]. However, after reaching a specific turning point, a further increase in income will be accompanied by an improvement in environmental quality, thus forming an inverted U-shaped curve.

The mechanism behind the EKC hypothesis can be explained through three effects: (1) Scale Effect, where an increase in the scale of economic activity will increase pollution; (2) Composition Effect, where the economic structure shifts from pollution-intensive industries to cleaner service and technology sectors; and (3) the Technique Effect, where prosperity drives the demand for a cleaner environment, which in turn triggers the adoption of environmentally friendly technologies [9]. Although the EKC hypothesis is widely accepted, its validity remains debated and varies across countries, pollutants, and time periods, suggesting that economic growth alone does not guarantee environmental sustainability.

The relationship between economic growth and CO_2 emissions is one of the most extensively researched topics in the field of environmental economics [7]. Several studies have examined the validity of the EKC hypothesis, yielding mixed results. Some studies have found evidence supporting the EKC hypothesis in developed countries [11, 12]. In contrast, other studies in developing countries, including Indonesia, often reveal a positive relationship, where economic growth consistently increases CO_2 emissions without a clear turning point [3, 6]. These mixed results suggest that contextual factors, including industrial structure, environmental policy, and technological level, play a crucial role.

There is a strong consensus in the literature that the transition to renewable energy is the most effective mitigation strategy [5]. Studies have consistently shown a negative relationship between renewable energy consumption and CO_2 emissions. Wuri et al. [5] and Madaleno and Nogueira [7] affirmed that increasing the share of renewable energy in the national energy mix significantly reduces the carbon footprint. Pambudi et al. [13] specifically highlighted the significant potential of renewable energy in Indonesia, while also underscoring the challenges associated with investment and infrastructure. Therefore, analysing the role of renewable energy is not only relevant but also crucial in the context of Indonesia's climate commitments.

The impact of trade openness on CO_2 emissions is more ambiguous, giving rise to two conflicting hypotheses. On the one hand, the pollution haven hypothesis posits that developed countries with stringent environmental regulations will relocate their polluting industries to developing countries with less stringent regulations, thereby increasing emissions in host countries. On the other hand, the halo effect hypothesis posits that international trade can facilitate cleaner and more efficient technology transfer, as well as encourage the adoption of global environmental standards, ultimately reducing emissions [7, 8]. Empirical evidence on which hypothesis is dominant in Indonesia is still inconclusive, so further analysis is needed.

Similar to trade, the role of FDI is also twofold. FDI can be an essential channel for transferring green technology, implementing modern management practices, and providing capital for environmentally friendly projects, which support emission reduction. However, FDI also has the potential to increase emissions if the investment is concentrated in extractive and energy-intensive manufacturing sectors without adequate environmental standards [9]. Studies by Liu and Wang [14] demonstrate that the type and origin of FDI significantly influence its environmental impact in the host country.

3. METHODOLOGY

To develop a dynamic model of CO_2 Emissions to achieve sustainable development, the ECM approach is used. The advantage of this ECM model is that it can analyze the dynamics of adjustments between variables that affect CO_2 emissions. The data used are annual statistics on the state of Indonesia for the period 2000-2023, which include CO_2 emissions, renewable energy consumption, economic growth, trade openness, and FDI, presented in detail in Table 1.

The dependent variables in this study are LCO_2 emissions, while the independent variables are renewable energy consumption, economic growth, trade openness, and LFDI.

a. Dynamic model approach

The dynamic model used in this study enables the interpretation of the long-term behaviour of economic variables, as economic theory generally explains the long-term relationships between economic variables [15, 16]. The results of the economic model estimation can be used as an analytical instrument for testing economic theory and estimating future values. In certain economies, reactions to specific actions often occur gradually over time [17].

Table 1. Data and data sources

Variable	Description	Unit	Expectations	Source
LCO_2	CO_2 emissions per capita	percent	-	Our World in Data
LREN	Renewable energy consumption	percent	negative	Our World in Data
LGrowth	GDP growth per capita (constant prices 2015)	percent	negative	World Development Indicators
LTrade	Trade openness is measured by the share of exports and imports of GDP	percent	negative	World Development Indicators
LFDI	Foreign Direct Investment inflows	percent	negative	World Development Indicators

The variation of dependent variables is determined not only by the variation of explanatory variables in the same period, but also by their variations in the past and in the future [15]. In this case, economic agents face an imbalance because the desired phenomenon is not necessarily the same as what happens and what is needed to adjust. Therefore, a model that is in tune with reality is dynamic. Since the reaction resulting from a rare action is instantaneous, the dynamic model then involves a lag variable in its analysis [10, 16].

b. ECM

The ECM model can encompass more variables in analysing both short-term and long-term economic phenomena, examine the consistency of empirical models with economic theory, and identify solutions to problems associated with nonstationary time series variables and spurious regressions in econometrics [18]. The ECM model is used to achieve equilibrium by minimising imbalance costs and adjustment costs [10, 15, 19].

c. ECM model specifications

$$\mathrm{DY}_t = \beta_0 + \beta_1\,\mathrm{DX}_t + \beta_2\,\mathrm{BX}_t + \beta_3\,\mathrm{B}(\mathrm{X}_t - \mathrm{Y}_t) + \varepsilon_t \quad (1)$$

where, $\mathrm{DX}_t = \mathrm{X}_t - \mathrm{X}_{t-1}$, $\mathrm{BX}_t = \mathrm{X}_{t-1}$, t = time trend and X_t is the observed variable in period t, and *B* is the backward lag operator.

Based on the basic ECM equation (Eq. (1)), the equation of the CO_2 emission model can be written as follows:

$$\begin{aligned}\mathrm{DLCO}_{2t} = {} & \beta_0 + \beta_1\mathrm{DLREN}_t + \beta_2\mathrm{DLGrowth}_t \\ & + \beta_3\mathrm{DLTrade}_t + \beta_4\mathrm{DLFDI}_t \\ & + \beta_5\mathrm{BLREN}_t + \beta_6\mathrm{BLGrowth}_t \\ & + \beta_7\mathrm{BLTrade}_t + \beta_8\mathrm{BLFDI}_t \\ & + \beta_9 B((\mathrm{LREN}_t + \mathrm{LGrowth}_t \\ & + \mathrm{LTrade}_t + \mathrm{LFDI}_t) - \mathrm{LCO}_{2t})) \\ & + \varepsilon_t\end{aligned} \quad (2)$$

where,

$\beta_1 \ldots \beta_9$ = Coefficient of the ECM equation,

LCO_2 = CO_2 emissions,

LREN = Renewable energy consumption,

LGrowth = Economic growth,

LTrade = Trading openness,

LFDI = Foreign Direct Investment.

From the above equation, it can be seen that economic actors made a marginal adjustment to the rate of LCO_2 emissions from $BLCO_2$ (LCO_2 in the t-1 period) in response to changes in independent variable components in the previous period. Coefficient $\beta_1 .. \beta_4$ can be used to see short-term effects, while other coefficients can describe long-term effects. Coefficient β_9 is ECT_{t-1} to see the speed of adjustment of economic agents to changes in economic policies. ECT is a lagged residual from the cointegrating relation. If the coefficient β_9 is statistically significant, sustainable development is achieved.

To obtain an equation that represents a long-term equilibrium relationship between variables, a cointegration approach is necessary, which involves a stationarity test consisting of a unit root test and a degree of integration [16, 20]. The cointegration approach can also be viewed as a test of economic theory and as a crucial component in the formulation and estimation of dynamic models [21].

The ECM can be derived directly from the form of Autoregressive Distributed Lag (ARDL) [2]. The form ARDL(p,q) in the level can be written as follows:

$$\mathrm{Y}_t = \alpha_0 + \sum_{i=1}^{p} \emptyset_i\, Y_{t-i} + \sum_{j=0}^{q} \beta'_{j_i}\, X_{t-j} + \varepsilon_t \quad (3)$$

By transforming to the first differential form and adding a long-term equilibrium component, the above model can be rewritten as a form of ECM:

$$\Delta\mathrm{Y}_t = \gamma_0 + \sum_{i=1}^{p-1} \gamma_i\, \Delta Y_{t-i} + \sum_{j=0}^{q-1} \delta'_j\, \Delta X_{t-j} + \lambda\mathrm{ECT}_{t-1} + \mu_t \quad (4)$$

The error correction term (ECT) represents the deviation from the long-term equilibrium in the previous period, ECT_{t-1}. The λ coefficient is expected to be negative and statistically significant, indicating the presence of an error correction mechanism that drives the system back to equilibrium. Thus, ECM allows for a clear separation between short-term influences and long-term relationships.

d. Unit root test

This test is considered a test of data stationarity. It is designed to determine whether a particular coefficient of an autoregressive model estimate has a value greater than one or not (in absolute terms). If the coefficient has a value of one or less, then the data is not stationary. The first step to be taken in this test is to assess the autoregressive model of each variable that will be used in the study as a test [15, 19]:

$$\mathrm{DX}_t = a_0 + a_1\mathrm{BX}_t + \textstyle\sum_{i=1}^{k} b_i \mathrm{B}_i \mathrm{DX}_t \quad (5)$$

$$\mathrm{DX}_t = c_0 + c_1 T + c_2\mathrm{BX}_t + \textstyle\sum_{i=1}^{k} d_i \mathrm{B}_i \mathrm{DX}_t \quad (6)$$

where, $\mathrm{DX}_t = \mathrm{X}_t - \mathrm{X}_{t-1}$, $\mathrm{BX}_t = \mathrm{X}_{t-1}$, t = time trend and X_t is the variable observed in period t, and *B* is a backward lag operator.

The second step is to calculate the statistical values of the Dickey-Fuller (DF) and Augmented Dickey-Fuller (ADF) tests. The values of DF and ADF are used to test the hypothesis that a1 = 0 and c2 = 0, indicated by the value of t in the coefficient BX_t from the equation above. The optimal lag is determined by the AIC/SBIC value in the STATA program

[5].

e. Integration degree test

If the data observed in the unit root test is not stationary, the next step is to perform the integration degree test. This test is performed to determine the degree or order of differentiation at which the observed data will be stationary [10]. The definition of data integration means that X time series data is integrated to degree d. The data needs to be differentiated up to d times to become stationary data or I(0) [15, 16, 22].

The first step in the integration test level is to estimate the autoregressive model by Ordinary Least Squares (OLS):

$$D^2\mathrm{X}_t = e_0 + e_1\mathrm{BDX}_t + \sum_{i=1}^{k} f_i \mathrm{B}_i D^2\mathrm{X}_\mathrm{t} \quad (7)$$

$$D^2\mathrm{X}_t = g_0 + g_1 T + g_2\,\mathrm{BDX}_t + \sum_{i=1}^{k} h_i \mathrm{B}_i D^2\mathrm{X}_\mathrm{t} \quad (8)$$

where, $\mathrm{D}^2\mathrm{X}_\mathrm{t} = \mathrm{DX}_t - \mathrm{DX}_{t-1}$, $\mathrm{BDX}_t = \mathrm{DX}_{t-1}$.

The values of DF and ADF in this test can be determined by examining the statistical value t in the regression coefficient of the above equation. If e_1 and g_2 are equal to one, then variable X is stationary at the first differential or integrated by one degree. If e_1 and g_2 are not different from zero, it means that the variable is not stationary at the first differential. In this case, the integration test level needs to be continued until stationary conditions are obtained BDX_t.

f. Cointegration test

The cointegration test is a continuation of the unit root and the degree of integration test. The method used is the Engle-Granger method. The cointegration test is designed to determine whether the residual regression is stationary [10, 15, 22]. To perform the cointegration test, it must be ensured that the observed variables have the same level of integration. If one or more variables have different degrees of integration, e.g., X = I(1) and Y = I(2), then they cannot be cointegrated.

g. Diagnostic tests

In addition to the above tests, diagnostic tests are also required to determine if the regression lines obtained can be effectively used to predict dependent variables. The tests carried out were normality tests, linearity tests, heteroscedasticity tests, and autocorrelation tests [10].

The results of the Jarque–Bera normality test indicate that the residual p-value is 0.173, so the null hypothesis that the residuals are normally distributed is not rejected. This indicates that the data support the assumption of residual normality. The results of the linearity tests, using the Ramsey RESET test, showed that the p-value was 0.332, indicating that the null hypothesis of adequate model specification was not rejected. In heteroscedasticity tests, we test whether the residual variance is constant using the Breusch–Pagan test. The test produced a p-value of 0.509, so the hypothesis of zero homoscedasticity was not rejected. This indicates that there is no significant heteroscedasticity in the final model. The results of the multicollinearity test using the Variance Inflation Factor (VIF) indicated a relatively low VIF value, well below the specified threshold, suggesting no multicollinearity.

4. RESULTS AND DISCUSSION

This section presents the comprehensive results of data analysis. The discussion began with descriptive statistics, followed by the results of the econometric prerequisite test. It concluded with an in-depth analysis of the short- and long-term model estimates and their implications.

4.1 Statistics descriptive

Table 2 presents descriptive statistics of the variables used in the study. The average CO_2 emissions per capita (LCO_2) during the study period were 0.604%, with a maximum value of 0.956% and a minimum value of 0.262%. The renewable energy consumption variable (LREN) showed an average value of 5.26%, with a maximum value of 0.6772% and a minimum value of 0.003%.

The economic growth variable has an average of 1.636 % with a maximum value of 1.848% and a minimum value of 1.292%. As for the trading openness variable, it has an average value of 3.888 % with a maximum value of 4.269% and a minimum value of 3.496%. The FDI variable has an average value of 0.394%, with a maximum value of 1.070% and a minimum value of -2.602%.

The highest variation is renewable energy consumption with a standard deviation value of 1.675%, indicating significant dynamics in the use of renewable energy in Indonesia during the 2000-2023 period. Other variables show a more moderate level of volatility.

4.2 Stationarity and cointegration test results

Before estimating the ECM model, a stationarity test was conducted using the root test of the Augmented Dickey-Fuller (ADF) unit to verify the level of integration of each variable. If the data observed in the unit root test is not stationary, the next step is to perform the integration degree test. This test is performed to identify the degree or order of differentiation of the observed data, which will be stationary [10].

The results of the ADF test are presented in Table 3. From the ADF test results, it can be seen that the variables of interest are not stationary at level I(0). The next step is to conduct an integration degree test to ensure that all variables become stationary at level I(1). This result is consistent with the PP test as an additional robustness test. These results meet the fundamental prerequisites for cointegration analysis and the formation of the ECM [20].

Table 2. Statistics descriptive

	LCO_2	LREN	LGrowth	LTrade	LFDI
Mean	0.603722	5.263277	1.636394	3.888472	0.394341
Median	0.641854	5.510951	1.619013	3.878631	0.602308
Maximum	0.955512	6.771935	1.847671	4.268814	1.070252
Minimum	0.262364	0.002996	1.292935	3.495664	-2.601643
Std. Dev.	0.206499	1.675495	0.143641	0.203998	0.815043
Skewness	0.059973	-2.598807	-0.737554	0.112236	-2.608975
Kurtosis	1.812657	8.729095	3.547972	2.252869	9.878478
Sum	24	24	23	24	21
Sum Sq.Dev	0.980759	64.56748	0.453918	0.957150	13.28590

Source: Authors' compilations

Table 3. The results of unit root test

Series	Model	ADF	ADF-P	PP	PP-P
At Level—I(0)					
LCO_2	Intercept and Trend	-3.556	0,0338	-3.093	0.108
LREN	Intercept and Trend	-0.979	0.7609	-0.873	0.959
LGrowth	Intercept and Trend	-3.604	0.0295	-3.607	0.029
LTrade	Intercept and Trend	-3.101	0.1060	-2.863	0.175
LFDI	Intercept and Trend	-5.236	0.0001	-3.669	0.025
At 1st difference—I(1)					
$DLCO_2$	Intercept and Trend	-5.403	0.0000	-7.942	0.000
DLREN	Intercept and Trend	-5.054	0.0002	-4.879	0.000
DLGrowth	Intercept and Trend	-7.385	0.0000	-9.388	0.000
DLTrade	Intercept and Trend	-4.686	0.0007	-6.675	0.000
DLFDI	Intercept and Trend	-7.508	0.0000	-7.864	0.000

Source: Authors' computations

Considering that all variables are integrated in the same order, i.e., I(1), a cointegration test is conducted. The cointegration test is a continuation of the unit root and the degree of integration test. The method used is the Engle-Granger method. The cointegration test is intended to test whether the residual regression produced is stationary [10, 15]. Additionally, the Engle-Granger cointegration test is conducted to verify the existence of a long-term equilibrium relationship. The results of the cointegration test indicated a cointegration relationship between the variables studied, making the use of ECM in this study methodologically valid.

4.3 Analysis of Error Correction Model estimation results

To estimate the long-term relationship and dynamics of short-term adjustments between renewable energy consumption, economic growth, trade openness, and FDI to CO_2 emissions in Indonesia, the ECM model was used. The results of the ECM model estimate can be seen in Table 4. The model exhibits good predictive ability, with an R-squared value of 0.8451, indicating that approximately 84.51% of the variation in CO_2 emissions can be explained by the independent variables in the model.

Table 4. ECM estimation results

Dependent Variable $dLCO_2$ Variable	Coefficient	Robust Standard Error	T-Statistic	Prob.
dLREN	-0.0658486	0.0192671	3.42	0.011
dLGrowth	0.3527136	0.323518	1.09	0.312
dLTrade	-1.12033	0.432994	2.59	0.036
dLFDI	0.1922286	0.047295	4.06	0.005
BLREN	-1.048658	0.4442375	2.36	0.050
BLGrowth	1.257463	0.6567419	1.91	0.097
BLTrade	-0.2863786	0.1813231	1.58	0.158
BLFDI	1.274315	0.4892095	2.60	0.035
ECT	-1.018277	0.4227763	2.41	0.047
Cons	5.324962	1.950175	2.73	0.029
R-squared	0.8451			
F-statistic	74.79			
Prob (F-statistic)	0.0000			
Root MSE	0.0802			

Source: Authors' computations

4.3.1 Short-term impact analysis

The results of ECM estimation indicate that in the short term, renewable energy (dLREN) and trade openness (dLTrade) significantly reduce CO_2 emissions [5, 7]. This can be seen from the renewable energy consumption coefficient of -0.066 and the significant trade openness coefficient of -1.120 at a 5% confidence interval. The negative impact of trade in the short term may indicate the existence of faster technology transfer or efficiency through the import of capital goods [23]. This can be interpreted to mean that, in the short term, the benefits of more efficient imports of capital goods and more advanced technologies are felt more quickly in reducing emissions, before the long-term structural impact of production specialisation becomes apparent. In contrast, foreign investment (dLFDI) shows a significant positive effect on CO_2 emissions in the short term [14, 24]. On the other hand, economic growth (dLGrowth) does not have a significant effect in the short term, indicating a time lag before the impact of economic growth is felt.

4.3.2 Long-term impact analysis

In the long term, renewable energy (BLREN) shows a coefficient of -1.0486 at a 5% significance level. This indicates that in the long run, a 1% increase in renewable energy consumption will reduce CO_2 emissions per capita by 1.0486%. These findings align with previous theories and studies that confirm the crucial role of renewable energy as a key pillar of decarbonization [4, 5, 7, 9].

The economic growth (BLGrowth) coefficient shows a value of 1.2574, indicating that in the long run, a 1% increase in GDP per capita will result in a 1.2574% increase in CO_2 emissions [2]. This indicates that Indonesia remains in a phase where economic growth has an increasing environmental impact and has not yet reached a turning point, as predicted by the EKC hypothesis [9]. The reversal of the EKC hypothesis has not yet been reached, indicating that the technique effect (adoption of clean technology) and composition effect (shift to the service industry) are not strong enough to compensate for the scale effect. In this case, the government should consider implementing the cap and trade policy [25].

Foreign investment (BLFDI) is seen to have a coefficient of 1.2743 with a significant level of 5%. This supports the pollution haven hypothesis. This implies that without strict environmental regulations and appropriate incentives, incoming FDI tends to be concentrated in carbon-intensive industries, thus contributing to increased emissions [26, 27]. Policies to attract FDI need to be balanced with clear green investment criteria to screen and direct investment to sectors that support sustainable development. The trading openness variable (BLTrade) does not exhibit a statistically significant long-term influence. This is because the positive effects of clean technology transfer through imports (the halo effect) are mutually negated by the negative effects of exporting carbon-dense products or relocating dirty industries [23].

4.3.3 Speed of adjustment: Implications for policy stability and effectiveness

The most prominent finding of the study is the ECT coefficient of −1.0182, which is negative and statistically significant. This indicates a very rapid adjustment toward the long-run equilibrium relationship between CO_2 emissions and its fundamental drivers, namely LREN, LGrowth, LTrade, and LFDI. Because the coefficient is about −1, the adjustment can be characterized as overshooting, meaning that when a shock pushes CO_2 away from its long-run path, the subsequent correction is strong enough to temporarily move the system beyond the equilibrium level before stabilizing. From a policy perspective, this suggests that well-designed energy and macroeconomic policies may translate into rapid changes in emissions outcomes. However, the same high speed of adjustment also implies a risk of short-run volatility: poorly calibrated policy shocks may trigger excessive fluctuations around the long-run path. Therefore, policy design should account not only for the long-run direction of effects through LREN, LGrowth, LTrade, and LFDI, but also for the economy's strong short-run response, to avoid unintended instability in the emissions adjustment process.

5. CONCLUSIONS

This study aims to analyse the short-term and long-term dynamic relationships between renewable energy consumption, economic growth, trade openness, FDI, and CO_2 emissions in Indonesia from 2000 to 2023. Using the ECM, this study provides new empirical evidence regarding the dynamics and speed of adjustment in Indonesia's economic and environmental systems.

The results of the analysis indicate that, in the short term, renewable energy and trade openness have a mitigating effect on emissions. The positive impact of trade in the short term suggests that the benefits of faster technology transfer through imports are evident. In the long term, renewable energy consumption has proven to be the most significant factor in reducing CO_2 emissions. Conversely, economic growth has been shown to increase CO_2 emissions significantly. The variable of FDI can increase CO_2 emissions in the short and long term, which confirms that Indonesia is still in a carbon-intensive development phase and supports the pollution haven hypothesis.

The error correction mechanism is the most crucial finding of this study, namely, the existence of a high-speed and overshooting error correction mechanism. This indicates that the economic and environmental systems in Indonesia are very responsive to shocks.

The results of the study have important policy implications for the Indonesian government in designing an effective sustainable development strategy, namely, (1) prioritising the acceleration of renewable energy. Given its substantial impact in reducing emissions, the government must place the energy transition as a top priority. The necessary policies include simplifying regulations, offering attractive fiscal incentives for renewable energy investors, and developing network infrastructure to support the intermittent integration of renewable energy sources. (2) FDI is sought to go towards the green sector. The results show that FDI contributes to increased emissions, serving as a strong signal for governments to reform their investment policies. It is necessary to implement strict green investment criteria, where investment incentives should be associated with environmental performance. Governments can create green investments to attract FDI to sectors that support low-carbon economies, such as electric vehicle manufacturing, energy efficiency, and the recycling industry. (3) Encourage green economic growth. The positive relationship between economic growth and emissions highlights the need for a paradigm shift from conventional growth to sustainable or green growth. Policies should be geared towards promoting clean technology innovation, supporting the circular economy, and implementing policy instruments such as carbon taxes or cap-and-trade to internalize the environmental costs of economic activities. And (4) prudent policy calibration. The high speed of system adjustment implies that policies must be designed and implemented with great care. Drastic policy changes can trigger unwanted volatility. A more gradual approach, accompanied by a strong monitoring and evaluation mechanism, is more advisable to ensure stability while still moving towards long-term goals.

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