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Asymmetric Effects of FDI and Energy Use on Environmental Degradation in Indonesia Using a Nonlinear Autoregressive Distributed Lag Approach

Putri Maulidar[1,*], Ricardo Marcão[2], Muksalmina Muksalmina[3], Ar Razy Ridha Maulana[4]

[1] Energy and Green Economics Unit, Graha Primera Saintifika, Aceh Besar 23371, Indonesia; putrimaulidar0@gmail.com.
[2] NECE-UBI, Universidade da Beira Interior, 6201-001 Covilhã, Portugal. ISLA Santarém - Polytechnic University, 2000-029 Santarém, Portugal; ricardo.marcao@islasantarem.pt.
[3] Department of Management, Faculty of Social Sciences and Education, Universitas Ubudiyah Indonesia, Banda Aceh 23114, Indonesia; muksalmina@uui.ac.id.
[4] Statistics of Aceh Province, Banda Aceh 23121, Indonesia; arrazy.ridha@bps.go.id.

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Abstract

This study examines the asymmetric effects of Foreign Direct Investment (FDI), economic growth, domestic capital formation, Renewable Energy Consumption (REC), and Fossil Energy Consumption (FEC) on carbon dioxide (CO2) emissions in Indonesia over the period 1970-2021. Using the Nonlinear Autoregressive Distributed Lag (NARDL) approach, the study examines whether FDI contributes to environmental degradation via the Pollution Haven Hypothesis (PHH) or improves environmental quality via the Pollution Halo Hypothesis. The results reveal strong evidence of asymmetric short-run and long-run relationships among the variables. Positive FDI shocks significantly increase CO2 emissions, while negative FDI shocks reduce emissions, indicating that FDI inflows in Indonesia are more consistent with the PHH. The findings further show that domestic capital formation and REC contribute to reducing CO2 emissions, whereas FEC remains a major driver of CO2 emissions. Economic growth is found to reduce emissions in the long run. These results highlight the importance of improving the environmental quality of FDI, strengthening green investment policies, accelerating renewable energy development, and reducing dependence on fossil fuels. The study provides policy-relevant evidence to align Indonesia's investment, energy, and environmental strategies toward sustainable, low-carbon development.

Keywords: Pollution haven, Pollution halo, Foreign direct investment, Energy consumption, Environmental quality.

1 | Introduction

Carbon dioxide (CO2) emissions have become one of the primary drivers of climate change and among the most critical environmental challenges of the twenty-first century [1], [2]. The expansion of industrial

Corresponding Author: putrimaulidar0@gmail.com
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production, rapid urbanization, fossil-fuel-based energy consumption, transportation growth, and land-use change have substantially increased atmospheric pressure and accelerated global warming [3], [4]. In many developing economies, this challenge is particularly complex because economic transformation remains closely linked to energy-intensive activities, infrastructure expansion, and reliance on coal, oil, and gas. As the dominant greenhouse gas associated with human economic activity, CO2 emissions contribute significantly to climate instability, rising temperatures, extreme weather events, and broader environmental degradation [5–7]. Consequently, reducing CO2 emissions has become a central priority in the global sustainable development agenda, especially for developing countries that must balance economic growth, industrial competitiveness, energy security, and environmental protection [8], [9].

In this context, Foreign Direct Investment (FDI) plays a crucial role in the development process. In the era of globalization, FDI serves as an important source of external financing and a driver of economic growth, especially in developing countries [10], [11]. Beyond increasing production capacity and employment, FDI can promote industrial modernization through technology transfer, productivity improvement, and better managerial practices. However, the environmental consequences of FDI remain highly debated in the environmental economics literature, particularly regarding whether foreign capital inflows increase or reduce CO2 emissions in host countries [12].

The literature generally explains the FDI–environment relationship through two competing hypotheses [12]. The first is the Pollution Haven Hypothesis (PHH), which argues that FDI may worsen environmental quality when multinational firms relocate pollution-intensive production activities to countries with relatively weak environmental regulations [13]. Under this view, developing countries may become destinations for carbon-intensive industries because of lower compliance costs and less stringent environmental enforcement. The second is the Pollution Halo Hypothesis, which suggests that FDI can improve environmental quality by introducing cleaner technologies, advanced production processes, higher environmental standards, and more efficient energy use in the host economy [14], [15]. Therefore, whether FDI contributes to environmental degradation or environmental improvement depends on the balance between pollution-intensive scale effects and cleaner technology-transfer effects.

Empirical evidence on the FDI–CO2 nexus remains mixed and context-specific [16]. These inconsistent findings suggest that the environmental impact of FDI is shaped by several country-specific factors, including economic development, industrial structure, energy composition, technological absorptive capacity, institutional quality, and the strength of environmental regulation [17]. For instance, Saqib et al. [16] found that FDI significantly reduces ecological footprint in high-income European economies, particularly where institutional quality and environmental regulations are strong. This finding supports the view that FDI can facilitate cleaner production and energy efficiency when supported by effective governance structures. However, other studies report heterogeneous or opposing results. Ahmad et al. [17] showed that FDI reduces emissions in more developed Chinese provinces but increases environmental degradation in less developed provinces, suggesting that the validity of the Pollution Haven or Pollution Halo Hypothesis depends on regional economic and institutional conditions. Similarly, Mert and Caglar [15] found that FDI increases CO2 emissions in Turkey in the long run, supporting the PHH in a context where energy-intensive industrial sectors dominate. Broader cross-country evidence also confirms this heterogeneity. Abbasi et al. [18] reported that FDI increases carbon emissions in lower-income Asian economies but contributes to emission reduction in upper-middle-income countries, implying that absorptive capacity, technological readiness, and environmental policy stringency are decisive in shaping the environmental outcomes of foreign investment. Taken together, the global literature suggests that the direction of the FDI–CO2 relationship is not universal but depends strongly on the structural characteristics of the host economy [19], [20].

Indonesia provides a particularly important case for examining this issue. As one of the largest developing economies in the world, Indonesia faces a persistent policy dilemma: attracting FDI to support economic growth and industrial development while simultaneously reducing CO2 emissions and achieving sustainable development targets [21], [22]. FDI inflows into Indonesia have been closely associated with manufacturing, energy, mining, and other resource-based sectors, which may generate two contrasting environmental effects. On one hand, foreign investment can expand industrial activity and fossil-energy demand, thereby increasing emissions. On the other hand, FDI may introduce cleaner technologies, improve production efficiency, and support environmental management practices [18], [23].

Existing evidence for Indonesia remains inconclusive. Yilanci et al. [22] found evidence supporting the PHH in Indonesia, suggesting that foreign investment in environmentally sensitive and resource-based sectors may increase emissions when environmental regulation and enforcement are insufficiently strong [24]. Regional and cross-country studies that include Indonesia also point to similar concerns. Zhu et al. [11], in an ASEAN-5 study, reported that FDI increases carbon emissions at higher emission quantiles, implying that additional foreign investment may intensify environmental degradation in countries with already high pollution levels. Likewise, evidence from developing and resource-dependent economies suggests that when fossil fuels dominate national energy systems, FDI may reinforce carbon-intensive production structures [3]. Given Indonesia's continued reliance on coal and extractive industries, the environmental impact of FDI is therefore especially relevant [25].

Despite these important findings, several gaps remain in the Indonesian literature. First, many studies focus mainly on the growth–energy–emissions nexus without explicitly testing whether FDI supports the PHH or the Pollution Halo Hypothesis within an integrated macroeconomic framework [18],[26]. Second, a large portion of the existing evidence is based on panel studies of ASEAN or developing countries, which may obscure Indonesia-specific structural characteristics [20]. Third, limited attention has been paid to models that simultaneously incorporate FDI, economic growth, domestic capital formation, REC, and FEC to explain CO2 emissions [27]. This argument is important because CO2 emission dynamics in Indonesia are not determined solely by FDI, but also by macroeconomic growth, physical investment represented by Gross Fixed Capital Formation (GFCF), and the composition of energy use, particularly the dominance of fossil fuels over renewable energy [28].

These gaps are significant because Indonesia is one of the major FDI recipients in Southeast Asia, with foreign investment concentrated in sectors closely linked to energy use and environmental pressures. At the same time, Indonesia remains highly dependent on fossil fuels, particularly coal, which continues to dominate the national energy mix. Rising CO_2 emissions over recent decades, therefore, raise an important policy question: does FDI in Indonesia worsen environmental degradation through pollution-intensive investment, or does it contribute to cleaner production through technology transfer and improved efficiency? Although several studies have examined economic growth, energy consumption, and emissions in Indonesia, empirical research that explicitly places FDI within the Pollution Haven and Pollution Halo framework remains relatively limited.

Therefore, this study aims to analyze the effect of FDI on CO_2 emissions in Indonesia by controlling for key macroeconomic and energy-related factors, including GDP, GFCF, REC, and FEC. More specifically, this study examines whether the FDI–CO_2 relationship in Indonesia provides stronger support for the PHH (Pollution-Halo Hypothesis) [29]. By focusing on Indonesia as a country-specific case, this study positions Indonesia not merely as another developing economy, but as a structurally important case where foreign investment, fossil-energy dependence, industrial expansion, and environmental sustainability intersect.

This study contributes to the environmental economics and sustainable development literature in several ways. First, it explicitly examines the impact of FDI on CO_2 emissions within the competing frameworks of the PHH and the Pollution Halo Hypothesis, thereby enriching empirical evidence on the still-debated FDI–environment relationship. Second, by focusing specifically on Indonesia, this study provides a country-level analysis of a developing economy characterized by strong dependence on fossil fuels, resource-based industries, and increasing environmental policy challenges. Third, the study integrates macroeconomic and energy factors, including GDP, GFCF, REC, and FEC, to provide a more comprehensive understanding of the channels through which FDI may affect environmental quality. The findings are expected to offer relevant policy implications for designing investment and environmental strategies that encourage cleaner FDI, strengthen low-carbon development, and support Indonesia's transition toward sustainable economic growth.

2 | Materials and Methods

2.1 | Theoretical Framework

This study is grounded in the PHH, which posits that FDI may increase environmental degradation when multinational firms relocate pollution-intensive production to countries with relatively weaker environmental regulations [30–32]. Within the broader trade–environment framework developed by [33], economic integration influences environmental quality through scale, technique, and composition effects. In developing economies, inward FDI frequently concentrates in manufacturing, extractive, and energy-intensive industries, potentially reinforcing scale and composition effects that expand fossil-energy demand and carbon emissions [34–37].

Under the PHH framework, increased FDI inflows are therefore expected to be positively associated with carbon CO_2 emissions. However, the environmental consequences of FDI may vary with the intensity of capital inflows. As foreign capital penetration deepens, the relative dominance of scale, technique, and composition effects may shift, potentially altering the marginal impact of FDI on emissions. This possibility motivates considering nonlinear relationships in the empirical specification. To accommodate this possibility, the empirical specification incorporates both FDI and its squared term (FDI^2), allowing the marginal environmental effect of capital inflows to vary across different levels of investment intensity.

Broader macroeconomic and structural factors also shape environmental outcomes. Economic growth reflects aggregate scale effects associated with expanding output, while GFCF captures domestic capital accumulation that may influence industrial capacity and energy demand independently of foreign investment. Moreover, the composition of energy use plays a critical role: FEC contributes directly to carbon emissions, whereas REC may mitigate environmental pressures.

Taken together, these relationships suggest that the FDI–environment nexus may exhibit both nonlinear and asymmetric dynamics, warranting an empirical approach capable of capturing variations across different levels of capital inflows and differences between expansionary and contractionary adjustments.

2.2 | Data and Variables

This study employs annual time-series data for Indonesia spanning 1970–2021 to examine the dynamic relationship among FDI, economic activity, energy consumption, and environmental degradation. CO_2 emissions, measured in million metric tons, serve as the dependent variable and proxy for environmental degradation, reflecting fossil-fuel-based industrial activity and energy intensity.

FDI, measured as net inflows as a percentage of GDP, constitutes the primary explanatory variable. To capture potential magnitude-based nonlinearities in the FDI–emissions nexus, the squared term of FDI (FDI^2) is included in the baseline long-run specification. In the asymmetric dynamic framework, FDI is further decomposed into cumulative positive and negative changes to distinguish between expansionary and contractionary capital-flow shocks.

Economic activity is proxied by the annual real GDP growth rate, capturing aggregate scale effects associated with output expansion. In the NARDL specification, GDP growth is likewise decomposed into positive and negative components to allow for asymmetric growth–environment interactions. GFCF, expressed in constant 2015 US dollars, controls for domestic capital accumulation that may independently influence industrial capacity and energy demand.

To explicitly model the energy transmission mechanism of emissions, the analysis distinguishes between REC and FEC, both measured in Terawatt-hours (TWh). This distinction enables identification of whether environmental pressures arise primarily from fossil-energy expansion or whether renewable energy helps mitigate emissions.

All variables are obtained from the World Development Indicators (WDI) database to ensure consistency and comparability across the sample period, except for REC and FEC, which are sourced from Our World in Data (OWID).

2.3 | Methods

Previous empirical studies examining the foreign FDI–environment nexus predominantly rely on conventional linear time-series frameworks, particularly the Autoregressive Distributed Lag (ARDL) cointegration approach [16], [38–45]. While the ARDL methodology enables simultaneous estimation of short-run dynamics and long-run equilibrium relationships [46], [47] it imposes symmetry in the adjustment process, assuming that positive and negative changes in explanatory variables exert effects of identical magnitude in absolute terms.

However, as discussed in the conceptual framework, the FDI–environment relationship may exhibit both nonlinear and asymmetric dynamics. The environmental impact of capital inflows may vary across different levels of investment intensity, and expansionary and contractionary movements may generate distinct adjustment patterns. A purely symmetric linear specification may therefore be insufficient to capture these complexities.

To address these issues, this study employs the Nonlinear Autoregressive Distributed Lag (NARDL) framework developed by [48]. The NARDL model allows for asymmetric short- and long-run dynamics through a partial-sum decomposition of explanatory variables into positive and negative changes. This framework permits simultaneous estimation of short-run and long-run asymmetries within a single-equation dynamic structure and has been widely applied in environmental economic research [15], [37], [49–52]. The specification further incorporates the quadratic form of FDI to allow the marginal environmental impact of capital inflows to vary across different levels of investment intensity. All explanatory variables are decomposed into cumulative positive and negative components, enabling the simultaneous examination of magnitude-based nonlinearities and directional asymmetries within a unified dynamic framework.

2.3.1 | Baseline Long-Run Model

To empirically assess the validity of the PHH in Indonesia, the long-run relationship among FDI, economic activity, energy consumption, and environmental degradation is specified as:

$$\mathrm{CO2_t} = \alpha_0 + \alpha_1 \mathrm{FDI_t} + \alpha_2 \mathrm{FDI_t^2} + \alpha_3 \mathrm{GDP_t} + \alpha_4 \mathrm{GFCF_t} + \alpha_5 \mathrm{REC_t} + \alpha_6 \mathrm{FEC_t} + \varepsilon_t, \quad \textbf{(1)}$$

where $\mathrm{CO2_t}$ denotes carbon dioxide (CO2) emissions, $\mathrm{FDI_t}$represents inward FDI inflows (as a percentage of GDP), and $\mathrm{FDI_t^2}$ captures potential nonlinearities in the marginal environmental impact of capital inflows. The quadratic specification allows the effect of FDI on emissions to vary across different levels of foreign capital penetration, accommodating the possibility that the relative dominance of scale, technique, and composition effects may change as investment intensity increases.

Economic growth ($\mathrm{(GDP)P_t}$) is included to account for scale effects associated with expanding output, while ($\mathrm{GFCF_t}$) reflects capital accumulation that may alter production capacity and energy demand. Renewable Energy Consumption ($\mathrm{REC_t}$) and Fossil Energy Consumption ($\mathrm{FEC_t}$) are incorporated separately to distinguish between cleaner and carbon-intensive energy sources.

Under the PHH, the expected sign of α_1 is positive, indicating that inward FDI increases emissions through scale and composition effects. FEC is expected to exert a positive effect on emissions, whereas REC is anticipated to reduce environmental degradation.

Although the quadratic term captures magnitude-based nonlinearities in the FDI–emissions relationship, it does not differentiate between expansionary and contractionary movements in FDI. That is, the quadratic specification allows the marginal impact of FDI to vary with its size but continues to impose symmetry across directions of change. To further account for potential directional asymmetries in environmental adjustment, the analysis employs the NARDL framework, which decomposes the explanatory variables into positive and negative partial sums.

2.3.2 | Asymmetric Decomposition and NARDL Framework

The nonlinear ARDL model developed by [48] extends the ARDL bounds-testing framework of [53] by allowing asymmetric decomposition of explanatory variables into positive and negative partial sums. This framework enables simultaneous estimation of short-run and long-run asymmetries within a single-equation dynamic specification.

To capture potential directional asymmetry, all explanatory variables are decomposed into cumulative positive and negative changes. For a generic variable X_tThe partial sum processes are defined as:

$$CO2_t = \alpha_0 + \alpha_1 FDI_t + \alpha_2 FDI_t^2 + \alpha_3 GDP_t + \alpha_4 GFCF_t + \alpha_5 REC_t + \alpha_6 FEC_t + \varepsilon_t, \quad (2)$$

By construction, each variable can be written as:

$$X_t = X_t^+ + X_t^-. \quad (3)$$

This decomposition allows increases and decreases in each regressor to exert distinct effects on CO_2 emissions, thereby identifying potential asymmetric cointegration relationships that may remain undetected under symmetric specifications.

The asymmetric error-correction representation of the fully decomposed NARDL model is specified as:

$$\begin{aligned}\Delta CO2_t = {} & \alpha_0 + \alpha_1 \ln CO2_{t-1} + \alpha_2^+ FDI_{t-1}^+ + \alpha_3^- FDI_{t-1}^- + \alpha_4^+ FDI_{t-1}^{2+} + \alpha_5^- FDI_{t-1}^{2-} + \alpha_6^+ GDP_{t-1}^+ \\ & + \alpha_7^- GDP_{t-1}^- + \alpha_8^+ \ln GFCF_{t-1}^+ + \alpha_9^- \ln GFCF_{t-1}^- + \alpha_{10}^+ \ln REC_{t-1}^+ + \alpha_{11}^- \ln REC_{t-1}^- \\ & + \alpha_{12}^+ \ln FEC_{t-1}^+ + \alpha_{13}^- \ln FEC_{t-1}^- + \sum_{i=1}^{p} \phi_{1i}\, \Delta \ln CO2_{t-i} + \sum_{i=0}^{q} \phi_{2i}^+\, \Delta FDI_{t-i}^+ \\ & + \sum_{i=0}^{q} \phi_{3i}^-\, \Delta FDI_{t-i}^- + \sum_{i=0}^{q} \phi_{4i}^+\, \Delta FDI_{t-i}^{2+} + \sum_{i=0}^{q} \phi_{5i}^-\, \Delta FDI_{t-i}^{2-} + \sum_{i=0}^{q} \phi_{6i}^+\, \Delta GDP_{t-i}^+ \\ & + \sum_{i=0}^{q} \phi_{7i}^-\, \Delta GDP_{t-i}^- + \sum_{i=0}^{q} \phi_{8i}^+\, \Delta \ln GFCF_{t-i}^+ + \sum_{i=0}^{q} \phi_{9i}^-\, \Delta \ln GFCF_{t-i}^- + \sum_{i=0}^{q} \phi_{10i}^+\, \Delta \ln REC_{t-i}^+ \\ & + \sum_{i=0}^{q} \phi_{11i}^-\, \Delta \ln REC_{t-i}^- + \sum_{i=0}^{q} \phi_{12i}^+\, \Delta \ln FEC_{t-i}^+ + \sum_{i=0}^{q} \phi_{13i}^-\, \Delta \ln FEC_{t-i}^- + \psi ECM_{t-1} + \varepsilon_t, \end{aligned} \quad (4)$$

where $\alpha_1 - \alpha_{13}$ denote the long-run coefficients of the lagged level variables, including the positive and negative partial-sum components of each explanatory variable. The terms $\sum_{i=0}^{q} \phi_{1i} - \sum_{i=0}^{q} \phi_{13i}$ represent the short-run dynamic coefficients, which also distinguish between positive and negative shocks in the first-differenced variables. Specifically, the superscripts (+) and (−) represent positive and negative shocks, respectively, allowing the model to capture asymmetric long-run effects of increases and decreases in FDI, FDI^2, GDP, GFCF, REC, and FEC on CO_2 emissions. Thus, the NARDL specification allows both long-run and short-run responses of CO_2 emissions to differ depending on whether the explanatory variables increase or decrease. The operator Δ denotes the first difference of the variables at period t, while p and q indicate the selected lag length. The coefficient ψ represents the error-correction term, which measures the speed of adjustment from short-run disequilibrium toward the long-run equilibrium. A negative and statistically significant ψ confirms the existence of a stable long-run relationship. Finally, ε_t denotes the stochastic error term.

2.3.3 | Unit Root Test

Before estimating the ARDL/NARDL specification, the time-series properties of the variables are examined to determine their integration orders. Identifying whether the variables are stationary in levels or in first differences is essential to avoid spurious regression and to ensure the validity of the bounds-testing procedure, which requires that variables be integrated of order zero (I(0)) or order one (I(1)), but not order two (I(2).

Stationarity is assessed using the Augmented Dickey–Fuller (ADF) test [54], based on the following specification:

$$\Delta y_t = \gamma y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta y_{t-i} + \varepsilon_t, \quad (5)$$

where the null hypothesis $H_0: \gamma = 0$ indicates the presence of a unit root. To enhance robustness against serial correlation and heteroskedasticity, the Phillips–Perron (PP) test is also applied [55]. The combined use of ADF and PP tests ensures reliable identification of the integration order of each variable before cointegration analysis.

2.3.4 | Autoregressive distributed lag bounds test for cointegration

Once the integration properties are confirmed and no variables are integrated of order 2, the existence of a long-run equilibrium relationship is assessed using the ARDL bounds-testing approach. In the unrestricted error-correction representation of the model, the null hypothesis of no cointegration corresponds to the joint insignificance of the lagged level variables:

$$H_0: \lambda_1 = \lambda_2 = \cdots = \lambda_8 = 0. \quad (6)$$

The calculated F-statistic is evaluated against the relevant critical value bounds. A statistic exceeding the upper bound indicates the presence of a stable long-run relationship, whereas a value below the lower bound implies the absence of cointegration. The empirical results of the unit root and bounds tests are reported and discussed in Section 3.

2.4 | Analytical Framework

Fig. 1 illustrates the sequential flow of the empirical analysis conducted in this study. The analysis begins with descriptive statistics to summarize the main characteristics of the variables, followed by unit root tests to identify the stationarity properties of the time-series data. After confirming that the variables are suitable for NARDL estimation, the optimal lag length is selected to ensure an appropriate dynamic model specification. The next step is the cointegration test, which examines whether a stable long-run relationship exists among CO_2 emissions, FDI, GDP, GFCF, REC, and FEC. Once cointegration is confirmed, the NARDL model is estimated to assess the asymmetric short-run and long-run effects of positive and negative shocks in the explanatory variables on CO_2 emissions. Finally, the analysis concludes with a summary of the main findings, policy implications, and research limitations.

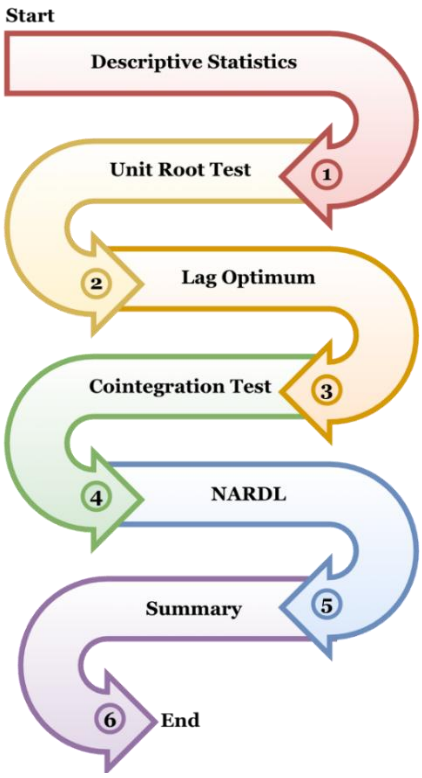


Fig. 1. Flowchart of the empirical analysis.

2.5 | Conceptual Framework of the Study

Fig. 2 presents the conceptual framework for explaining the asymmetric relationship among FDI, FDI^2, GDP, GFCF, REC, FEC, and CO_2 emissions in Indonesia. The framework shows that each explanatory variable may affect CO_2 emissions through positive and negative shocks, reflecting the NARDL approach used in this study. Positive shocks represent increases in the variables, while negative shocks represent decreases, allowing the model to capture whether the environmental effects differ depending on the direction of change. FDI and FDI^2 are expected to have either positive or negative effects on CO_2 emissions, depending on whether foreign investment supports pollution-intensive activities or promotes cleaner technology transfer. GDP and GFCF may also have mixed effects, as economic growth and capital formation can either increase emissions through higher production and energy demand or reduce them through structural transformation and efficiency improvements. REC is expected to reduce CO_2 emissions, whereas FEC is expected to increase emissions due to its carbon-intensive nature.

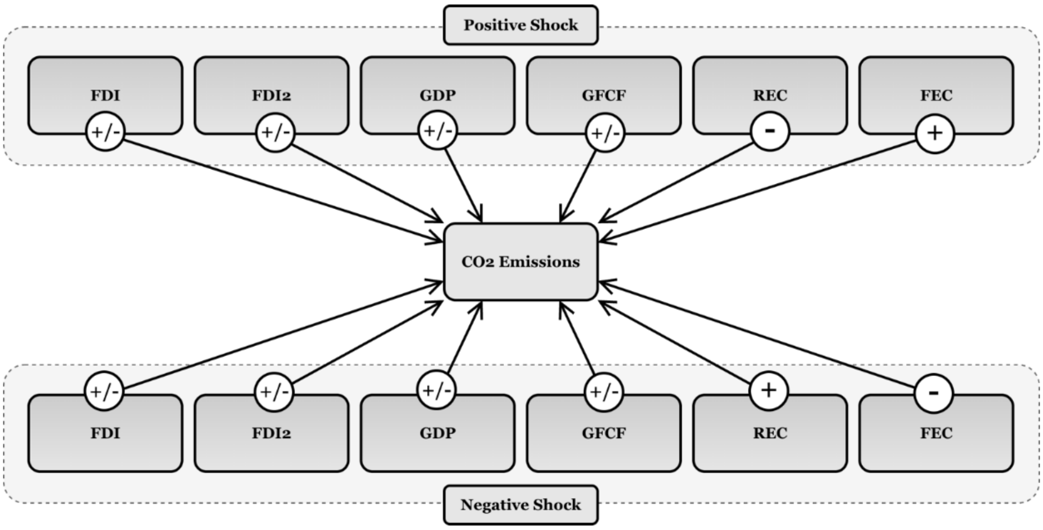


Fig. 2. Conceptual framework of asymmetric positive and negative shocks on CO_2 emissions in the NARDL model.

3 | Results and Discussion

3.1 | Descriptive Statistics

The descriptive statistics presented in *Table 1* indicate that CO_2 emissions in Indonesia average 268.1 million tons, with a wide dispersion ranging from 35.8 to 659.4 million tons and a standard deviation of 186.7 million tons, reflecting substantial variability in environmental outcomes. FDI averages 1.23 percent of gross domestic product, ranging from –2.76 percent to 4.24 percent. At the same time, the squared term of FDI has a higher mean of 3.17 and reaches a maximum of 17.99, suggesting potential nonlinear effects during periods of large capital fluctuations. Economic growth averages 5.38 percent, indicating consistent expansion, although volatility is evident with a minimum of –13.13 percent and a standard deviation of 3.30. GFCF, expressed in constant 2015 United States dollars, records a high mean of 128.9 billion and spans from 9.18 to 349 billion, reflecting wide cycles in investment intensity. REC averages 46.49 terawatt hours, ranging from 3.14 to 239 terawatt hours, illustrating upward yet uneven adoption of renewable energy. In contrast, FEC averages 950.79 terawatt hours, with a maximum of 2,109 terawatt hours and a standard deviation of 649.43, highlighting the continued dominance of fossil energy in the national energy mix. Overall, these figures capture the dynamic interactions among growth, investment, energy structure, and emissions, providing the empirical foundation for the study's analysis.

Table 1. Descriptive statistics

Variable	Mean	Median	Max.	Min.	Std. Dev.
CO2 (million ton)	268,095,378	220,357,010	659,435,700	35,791,384	186,721,936
FDI (%)	1.2282	1.2695	4.2413	-2.7574	1.3011
FDI^2 (%)	3.1688	1.8717	17.9885	0.0055	3.6502
GDP (growth %)	5.3796	5.8278	9.8801	-13.1267	3.2974
GFCF (constant USD 2015)	128,939,653,513	105,353,983,017	349,049,205,922	9,180,215,013	101,634,356,374
REC (TWh)	46.4937	31.2024	238.9787	3.1363	54.1522
FEC (TWh)	950.7854	869.9432	2,109.2285	94.5803	649.4327

3.2 | Unit Root Test

Table 2 reports the ADF and P-P unit-root tests. The results indicate a mixture of I(0) and I(1) variables. FDI, FDI^2, GDP, and FEC are stationary in levels under the ADF test, while CO_2, GFCF, and REC require first differencing in at least one test. The PP test provides additional evidence that several variables are stationary in levels, including CO_2 and GFCF. Most importantly, all variables become stationary after first differencing, and none is integrated of order 2. The integration pattern, therefore, supports the use of the ARDL/NARDL bounds-testing framework.

Table 2. Unit root test results.

Variable	ADF		P-P	
	t-stat.	**Prob.**	**t-stat.**	**Prob.**
Level				
CO2	-2.2452	0.1935	-4.4254***	0.0008
FDI	-3.3884**	0.0160	-3.3804**	0.0163
FDI2	-5.7944***	0.0000	-5.9477***	0.0000
GDP	-5.0079***	0.0001	-5.0079***	0.0001
GFCF	-2.3758	0.1537	-2.9002*	0.0523
REC	0.3408	0.9783	0.3408	0.9783
FEC	-4.6879***	0.0004	-4.5886***	0.0005
1st diff				
CO2	-5.8927***	0.0000	-6.3744***	0.0000
FDI	-9.8893***	0.0000	-9.8893***	0.0000
FDI2	-5.0084***	0.0001	-26.6642***	0.0001
GDP	-7.8742***	0.0000	-23.6158***	0.0001
GFCF	-5.1508***	0.0001	-4.7081***	0.0003
REC	-10.3991***	0.0000	-10.6367***	0.0000
FEC	-5.2480***	0.0001	-5.4358***	0.0000

Note: ** (5%) and *** (1%).

3.3 | Autoregressive distributed lag bounds test for cointegration

The bounds test results in *Table 3* confirm the presence of a long-run relationship among the variables. The calculated F-statistic is 5.5358, which exceeds the upper-bound critical value at the 1% level. The null hypothesis of no level relationship is therefore rejected. This evidence supports estimation of the NARDL error-correction model. The optimal lag structure should be explicitly reported in the final version, as the current draft includes a figure placeholder but does not state the selected lag order in the text.

Table 3. ARDL Bound Test Results.

F-Bounds Test		Null Hypothesis: No linear relationship		
Test stat.	**Value**	**Signif.**	**I(0)**	**I(1)**
F-stat.	5.5358	10%	1.76	2.77
K	8	5%	1.98	3.04
		1%	2.41	3.61

3.4 | Optimal Lag Length Selection

The optimal lag length was selected using the information criterion, with the model yielding the lowest value preferred. As shown in *Fig. 3*, the lag specification (2,2,2,2,2,1,2,2,1,2) has the lowest criterion value, approximately 3.98, and is therefore chosen for the NARDL estimation. This lag structure captures both immediate and delayed effects of FDI, economic growth, capital formation, and energy consumption on CO_2 emissions while maintaining model parsimony.

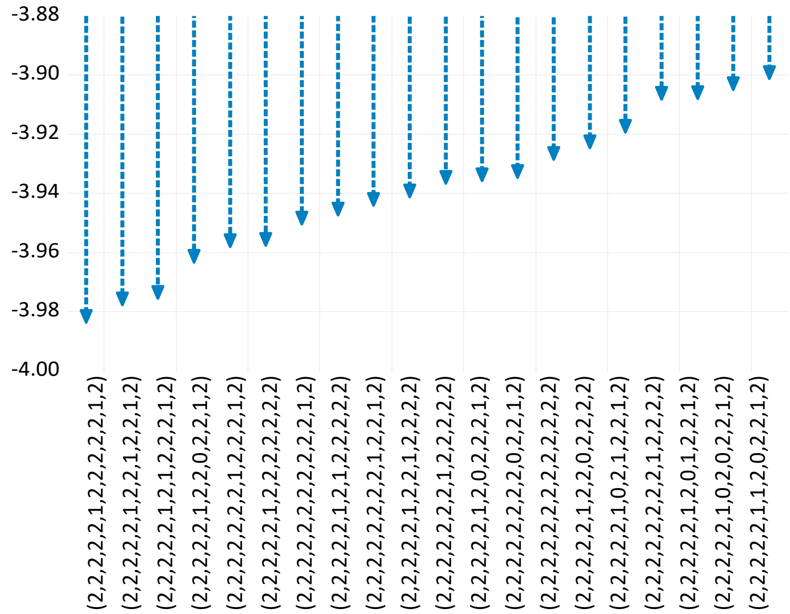


Fig. 3. Lag optimum results.

3.5 | ARDL-ECM Estimation

Before interpreting the estimated coefficients, the NARDL results should be understood as capturing both the long-run equilibrium effects and short-run dynamic adjustments of the explanatory variables on CO_2 emissions in Indonesia. The model decomposes FDI, GDP, GFCF, REC, and FEC into positive and negative shocks, enabling analysis of whether increases and decreases in these variables affect environmental degradation differently. The estimated long-run and short-run coefficients are presented in *Table 4*. In contrast, the corresponding asymmetric long-run responses are shown in Fig. 4. This provides a basis for evaluating the Pollution Haven and Pollution Halo hypotheses, as well as the roles of economic growth, domestic investment, and the energy structure in shaping Indonesia's CO_2 emission dynamics.

Table 4. NARDL estimation results for long-run and short-run coefficients.

Variable	Coeff.	Std. err.	t-stat.	Prob.
Long-run				
FDI^+	0.0954***	0.0163	5.8600	0.0000
FDI^-	-0.2795***	0.0527	-5.3047	0.0000
FDI^{2+}	0.0221**	0.0098	2.2610	0.0299
FDI^{2-}	0.0933***	0.0153	6.0976	0.0000
GDP^+	-0.0366***	0.0115	-3.1888	0.0030
GDP^-	-0.0276***	0.0090	-3.0541	0.0042
$GFCF^+$	-0.4774**	0.1774	-2.6910	0.0107
$GFCF^-$	1.4729***	0.4492	3.2792	0.0023
REC^+	-0.2123***	0.0649	-3.2710	0.0024
REC^-	0.8959***	0.1735	5.1648	0.0000
FEC^+	1.9985***	0.2483	8.0494	0.0000
FEC^-	-2.1030**	0.8434	-2.4934	0.0174
C	18.6384***	0.2174	85.7489	0.0000

Table 4. Continued.

Variable	Coeff.	Std. err.	t-stat.	Prob.
Short-run				
ECT (-1)	-1.3312***	0.1089	-12.2256	0.0000
ΔFDI^+	0.1527***	0.0212	7.2133	0.0000
$\Delta FDI^+(-1)$	0.2134***	0.0247	8.6479	0.0000
ΔFDI^-	-0.2098***	0.0323	-6.5039	0.0000
$\Delta FDI^-(-1)$	-0.2081***	0.0258	-8.0697	0.0000
ΔFDI^{2+}	-0.0381***	0.0046	-8.2937	0.0000
$\Delta FDI^{2+}(-1)$	-0.0874***	0.0104	-8.4050	0.0000
ΔFDI^{2-}	0.0568***	0.0095	5.9589	0.0000
$\Delta FDI^{2-}(-1)$	0.0438***	0.0061	7.1917	0.0000
ΔGDP^+	-0.0221***	0.0054	-4.0966	0.0003
ΔGDP^-	-0.0043	0.0029	-1.4797	0.1505
$\Delta GDP^-(-1)$	0.0273***	0.0037	7.2853	0.0000
$\Delta GFCF^+$	-0.2978***	0.0816	-3.6498	0.0011
$\Delta GFCF^-$	1.9030***	0.1845	10.3127	0.0000
$\Delta GFCF^-(-1)$	-0.5198***	0.1527	-3.4043	0.0021
ΔREC^+	0.0540*	0.0311	1.7349	0.0942
$\Delta REC^+(-1)$	0.2245***	0.0350	6.4095	0.0000
ΔREC^-	0.2475***	0.0581	4.2597	0.0002
$\Delta REC^-(-1)$	-0.8127***	0.1023	-7.9449	0.0000
ΔFEC^+	0.6683***	0.1329	5.0305	0.0000
ΔFEC^-	-0.2582	0.2826	-0.9136	0.3690
$\Delta FEC^-(-1)$	1.8876***	0.3398	5.5548	0.0000
R^2	0.9603			
Adj. R^2	0.9295			

Note: * (10%), ** (5%), and *** (1%).

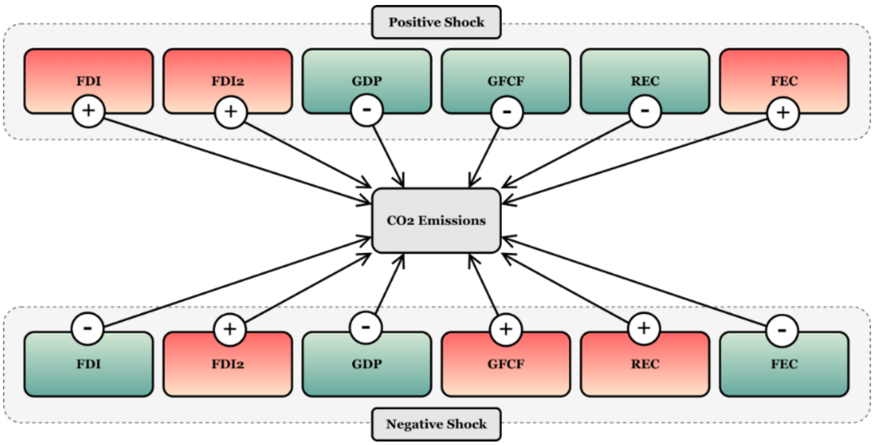


Fig. 4. Graphical results of NARDL long run.
Note: Red boxes indicate emission-increasing effects; green boxes indicate emission-reducing effects.

3.5.1 | The impact of FDI and FDI^2 on CO_2 emissions

The NARDL results show that FDI has significant asymmetric and nonlinear effects on CO_2 emissions in Indonesia. In the long run, positive FDI shocks increase environmental degradation, as indicated by the positive and statistically significant coefficient of FDI^+. Specifically, a 1% increase in FDI is associated with a 0.0954% increase in CO_2 emissions, while a 1% decrease in FDI reduces CO_2 emissions by 0.2795%, with both effects significant at the 1% level. This asymmetric pattern suggests that increases and decreases in FDI do not affect environmental quality to the same magnitude. More importantly, the result supports the PHH, indicating that FDI inflows in Indonesia may still be associated with pollution-intensive and energy-intensive sectors, such as mining, manufacturing, palm oil processing, energy, and other resource-based industries. In this context, foreign capital inflows may expand industrial production and fossil fuel demand, thereby increasing CO2 emissions when environmental regulations, technology transfer requirements, and green investment standards are not sufficiently strong.

The short-run results also confirm the asymmetric effect of FDI on CO_2 emissions. Positive FDI shocks increase environmental degradation in both the current and lagged periods, with coefficients of 0.1527 and 0.2134, respectively. In contrast, negative FDI shocks reduce emissions by 0.2098% in the current period and 0.2081% in the lagged period. These findings indicate that the environmental effects of FDI occur not only in the long run but also through immediate short-run adjustments. This argument may reflect the rapid response of industrial activity, production expansion, and energy demand following changes in foreign investment inflows. Therefore, the results suggest that FDI in Indonesia has not yet fully served as a channel for the diffusion of cleaner technologies, as proposed by the Pollution Halo Hypothesis. Instead, the dominant evidence indicates that FDI tends to increase environmental pressure, particularly when investment flows into sectors with high carbon intensity.

The significance of the FDI squared terms further indicates that the FDI–CO_2 relationship is nonlinear. In the long run, FDI^{2+} has a positive and significant effect on CO_2 emissions, implying that the environmental impact of FDI becomes stronger as the scale or intensity of foreign investment increases. Meanwhile, FDI^{2-} is also positive and significant, suggesting that the environmental response to changes in FDI is not simply linear or proportional. These results imply that the marginal environmental effect of FDI may vary with the magnitude and direction of foreign investment flows. In the short run, the coefficients of FDI^2 show mixed effects: positive changes in FDI^2 reduce emissions, while negative changes increase them. This short-run pattern may reflect temporary adjustment processes, investment volatility, production restructuring, or delayed responses to environmental compliance requirements. However, the long-run evidence clearly suggests that larger FDI movements can intensify environmental pressure when strict environmental standards and low-carbon technology requirements do not support foreign investment.

Overall, the findings for FDI and FDI^2 demonstrate that the relationship between foreign investment and CO_2 emissions in Indonesia is both asymmetric and nonlinear. The positive effect of FDI^+ and the emission-reducing effect of FDI^- provide strong evidence in favor of the PHH. At the same time, the significant FDI^2 coefficients indicate that the environmental consequences of FDI depend not only on whether FDI increases or decreases, but also on the scale of investment changes. These results imply that Indonesia should not focus solely on attracting higher volumes of FDI, but also on improving the quality and environmental orientation of foreign investment. Policy efforts should prioritize green FDI, cleaner technology transfer, stricter environmental screening, carbon reporting, and incentives for low-carbon industries. These findings are consistent with [12], [18], [56–58], which provide evidence of pollution haven effects in developing economies.

3.5.2 | The impact of GDP and GFCF on CO_2 emissions

Economic growth (GDP) negatively affects environmental quality in both directions: a 1% increase in GDP reduces environmental degradation by 0.0366%, and a 1% decrease in GDP reduces it by 0.0276%, both significant at the 1% level. Regarding domestic investment in GFCF, a 1% increase improves environmental quality by reducing degradation by 0.4774%. In contrast, a 1% decrease in GFCF increases degradation by 1.4729%, implying a stronger negative impact when capital formation contracts. In the short run, GDP increases reduce environmental degradation by 0.0221%, but GDP decreases are significant only in the lagged term, where a 1% decrease increases degradation by 0.0273%.

GDP growth shows a counterintuitive but favorable effect on environmental quality in Indonesia. In the long run, both positive and negative shocks to GDP reduce environmental degradation (–0.0366% and –0.0276%, respectively), suggesting that improvements in environmental quality may occur regardless of the direction of growth [59]. This argument may reflect Indonesia's structural transition toward services, education, and digital sectors, which are less environmentally intensive. In the short run, positive GDP changes reduce degradation by 0.0221%, while negative changes are significant only in the lagged term, where a 1% decrease leads to a 0.0273% increase in degradation. These results suggest that economic slowdowns can temporarily worsen environmental conditions, possibly due to increased reliance on low-cost, less efficient energy sources during downturns. Nevertheless, the long-run pattern hints at a potential decoupling of growth from pollution, especially if sustainable growth policies are strengthened. Sim ilar evidence was also reported by [18], [60–62].

The impact of capital formation on environmental quality is highly asymmetric and significant, reflecting the role of domestic investment in shaping sustainable outcomes. In the long run, a 1% increase in GFCF reduces environmental degradation by 0.4774%, indicating that investment in infrastructure and industry may support cleaner technologies and more efficient systems. However, a 1% decrease in GFCF increases degradation by 1.4729%, suggesting that lack of investment can cause substantial environmental harm—possibly due to delayed maintenance, outdated technology, or halted renewable energy projects. In the short run, positive GFCF shocks reduce degradation by 0.2978%, while negative shocks increase it by 1.9030%, with a corrective lag of –0.5198%. This argument underlines the urgent need for consistent investment in capital stock, especially in energy-efficient technologies and public infrastructure that mitigates pollution. The present findings corroborate the results documented by [63–65].

3.5.3 | The impact of energy consumption on CO2 emissions

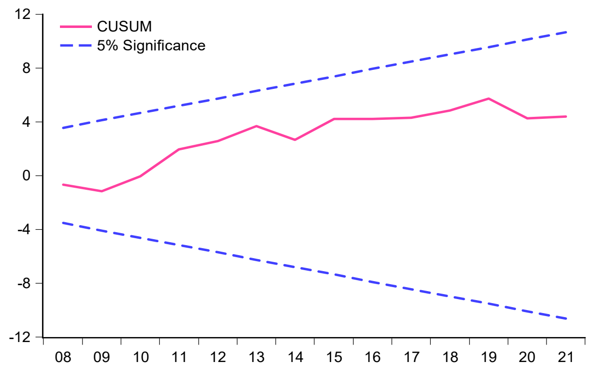
Energy variables also display clear asymmetries. A 1% increase in renewable energy (REC) reduces environmental degradation by 0.2123%, while a 1% decrease in REC significantly increases degradation by 0.8959%. Conversely, FEC deteriorates environmental quality: a 1% increase in FEC raises degradation by 1.9985%, while a 1% decrease in FEC improves the environment by 2.1030%. Furthermore, in the short run, renewable energy slightly raises degradation by 0.0540% in the current period and 0.2245% in the lag (both significant), while reductions in renewable energy raise degradation by 0.2475%, followed by a strong correction of -0.8127% in the lag. For fossil fuels, a 1% increase in degradation by 0.6683%, while decreases are not significant in the current period but become strongly positive in the lag, with a 1.8876% increase in degradation.

Renewable energy use plays a critical role in Indonesia's environmental improvement. In the long run, a 1% increase in REC reduces environmental degradation by 0.2123%, while a 1% decrease increases it by 0.8959%, showing clear asymmetry. This argument underscores the importance of expanding and protecting Indonesia's renewable energy initiatives, such as solar, hydro, and geothermal projects, especially given the country's significant renewable energy potential and its strategic commitments to reduce emissions. In the short run, the effect is mixed: current increases in REC slightly raise degradation by 0.0540%, but this is more than offset in the lag (–0.2245%), possibly reflecting adjustment periods or implementation delays. Decreases in REC, however, significantly increase degradation by 0.2475% initially, followed by a sharp lagged correction of –0.8127%, likely indicating the rebound effects of renewable project cycles or supply fluctuations. These dynamics underscore the need for sustained, uninterrupted investment in and use of renewables to sustain long-term environmental gains. This outcome aligns with the study conducted by [66–69].

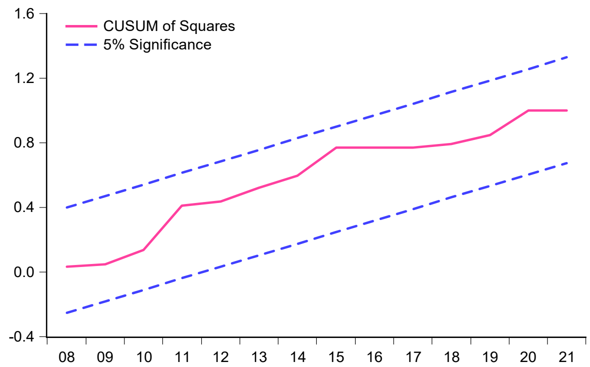
Fossil fuel consumption remains a primary driver of environmental degradation in Indonesia. In the long run, a 1% increase in FEC increases degradation by 1.9985%, while a 1% decrease reduces it by 2.1030%. These large and symmetric effects reflect the heavy reliance on coal and diesel in the national energy mix and the limited penetration of clean alternatives. In the short run, the impact of increased FEC is immediate and significant at 0.6683%, while contemporaneous reductions are not significant, but the lagged term shows a substantial 1.8876% increase in degradation. This surprising lag effect may reflect temporary disruptions or switching back to dirtier alternatives during energy transitions. The results clearly highlight the environmental cost of fossil fuel dependence and the urgency for Indonesia to accelerate its energy transition roadmap, including phasing out coal, improving energy efficiency, and scaling up renewables. This result is consistent with the findings of [67], [70–72].

3.6 | Diagnostic Tests for the ARDL-ECM Model

The diagnostic tests in *Table 5* indicate that the estimated model is statistically adequate. The Jarque-Bera test suggests normally distributed residuals, while the Breusch-Godfrey LM test provides no evidence of serial correlation at conventional levels. The Breusch-Pagan-Godfrey, Harvey, Glejser, and ARCH tests indicate no heteroskedasticity or ARCH effects. The Ramsey RESET test supports the functional-form adequacy assumption. CUSUM and CUSUMSQ stability should be reported graphically by confirming that the test statistics remain within the 5% critical bounds (displayed in *Fig. 5*).



a.



b.

Fig. 5. A. CUSUM and b. CUSUMQ results.

Table 5. The diagnostic test results.

Diagnostic tests	Coeff.	Prob.	Conclusion
Jarque-Bera	0.7446	0.6891	Residuals are normally distributed.
CUSUM	-	< 0.05	The model is stable
CUSUMQ	-	< 0.05	The model is stable
Breusch-Godfrey LM test	3.2838	0.0931	No serial correlation exists.
Breusch-Pagan-Godfrey test	0.7292	0.7800	No heteroscedasticity exists
Harvey test	1.2554	0.3337	No heteroscedasticity exists
Glejser test	0.9308	0.5876	No heteroscedasticity exists
ARCH test	0.1415	0.7086	No heteroscedasticity exists
Ramsey test	0.7722	0.4538	The model is properly specified.

4 | Summary

4.1 | Conclusions

This study examines the asymmetric effects of FDI, economic growth, domestic capital formation, REC, and FEC on CO_2 emissions in Indonesia using the NARDL approach. The empirical findings provide strong evidence of asymmetric short-run and long-run relationships among the variables. In particular, positive FDI shocks increase CO_2 emissions, while negative FDI shocks reduce emissions, indicating that FDI inflows in Indonesia are more consistent with the PHH than the Pollution Halo Hypothesis. It suggests that foreign investment may still be concentrated in energy-intensive and pollution-generating sectors, making environmental regulation and investment quality crucial for sustainable development.

The results also show that domestic capital formation and REC play an important role in reducing environmental degradation. Positive shocks in GFCF and REC are associated with lower CO_2 emissions, implying that investment in productive capital, infrastructure, and cleaner energy systems can support environmental improvement. In contrast, FEC remains a major driver of emissions, as increases in FEC significantly worsen environmental quality. The findings further indicate that GDP growth has a long-run emission-reducing effect, suggesting a possible shift toward partial decoupling between economic growth and environmental degradation. Overall, the results confirm that Indonesia's environmental outcomes are shaped not only by the volume of investment but also by its quality, the structure of economic activity, and the composition of energy consumption.

4.2 | Policy Recommendations

The findings have several important policy implications. Since FDI is found to increase CO_2 emissions, Indonesia should shift from a quantity-oriented FDI strategy toward a quality-oriented investment framework. Foreign investment should be directed toward cleaner industries, low-carbon technologies, renewable energy projects, and environmentally responsible production systems. This argument can be achieved by strengthening environmental screening for foreign investors, enforcing stricter emission standards, requiring environmental impact assessments, and promoting green technology transfer. Fiscal incentives, tax reductions, or preferential treatment should be given to foreign firms that adopt clean technologies, improve energy efficiency, and comply with carbon reporting requirements.

The significant role of GFCF in reducing emissions also indicates that domestic investment should be continuously supported, particularly in sustainable infrastructure, public transportation, renewable energy facilities, and energy-efficient industrial technology. At the same time, the contrasting effects of renewable and FEC highlight the urgency of accelerating Indonesia's energy transition. Policy measures should focus on expanding renewable energy capacity, reducing dependence on coal and other fossil fuels, improving grid infrastructure, and gradually reforming fossil-fuel subsidies. A coordinated policy framework linking investment policy, industrial development, energy planning, and environmental regulation is essential to ensure that economic growth and FDI inflows contribute to sustainable, low-carbon development.

4.3 | Limitations and Suggestions for Future Research

Although this study provides important empirical evidence on the asymmetric relationship between FDI and CO_2 emissions in Indonesia, several limitations should be acknowledged. First, the analysis uses aggregate national-level data, which may not fully capture sectoral differences in the environmental effects of FDI. Foreign investment in mining, manufacturing, agriculture, services, and renewable energy may have different impacts on emissions. Second, environmental quality is measured only by CO_2 emissions. Although CO_2 is a widely used indicator of environmental degradation, it does not fully represent other environmental problems such as deforestation, air pollution, water pollution, biodiversity loss, and ecological damage. Third, although the NARDL approach is suitable for identifying asymmetric short-run and long-run effects, the model does not explicitly account for structural breaks, policy regime changes, or major external shocks that may influence

Indonesia's emissions path. In addition, institutional factors such as environmental regulation, governance quality, and policy enforcement are not included in the model, even though they may strongly determine whether FDI produces pollution-haven or pollution-halo effects.

Future research could extend this study in several ways. Sector-level analysis would provide a more detailed understanding of how FDI affects emissions across different industries. Future studies may also include broader environmental indicators, such as ecological footprint, deforestation, particulate emissions, or energy intensity, to obtain a more comprehensive measure of environmental quality. Methodologically, future research could apply threshold models, structural break tests, time-varying parameter models, or regime-switching approaches to capture changes in policy, technology, and investment behavior over time. Comparative studies involving ASEAN or other developing economies would also be useful to examine how institutional quality and environmental regulation influence the FDI–environment relationship. Finally, incorporating governance and environmental policy indicators would help clarify the conditions under which FDI contributes to either environmental degradation or cleaner, more sustainable development.

Authors' Contributions

P. M.: Writing-original draft, Methodology, Data Curation, Conceptualization, Software, and Visualization, Writing-Review & Editing, and Validation. R. M.: Validation, Writing-Review & Editing, and Formal Analysis. M. M.: Writing-Review & Editing, Formal Analysis, and Investigation. A. R. R. M.: Writing-Review & Editing, Formal Analysis, and Investigation. The authors have read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

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