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Fuel Exports, Energy Consumption, and Industrial Emissions as Determinants of the Ecological Footprint in Indonesia

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ABSTRACT

Indonesia's continued reliance on fossil fuels links energy trade and domestic energy use to increasing ecological pressure. This study investigates the short- and long-run effects of fuel exports, domestic energy consumption, and energy-industry carbon emissions on Indonesia's ecological footprint from 1993 to 2022. Annual time-series data are analyzed using the autoregressive distributed lag (ARDL) technique, which accommodates variables integrated at I(0) and I(1) and captures both short-run dynamics and long-run relationships. Nevertheless, because the specification uses first-differenced series, re-estimation in levels is required before these estimates can establish long-run ecological-footprint relationships. The findings show that fuel exports are positively associated with the ecological footprint in both horizons, although their effects are weaker than those of domestic energy consumption. Domestic energy consumption exhibits the strongest positive and statistically significant long-run effect, highlighting fossil-based energy use as a major driver of ecological pressure. Energy-industry carbon emissions have no significant long-run effect, while their lagged short-run coefficient is negative and significant, suggesting a delayed adjustment process. The negative and significant error-correction term confirms convergence toward long-run equilibrium. These findings suggest that the Ministry of Energy and Mineral Resources should accelerate the transition to lower-carbon domestic energy use, the Ministry of Trade should incorporate environmental considerations into fuel-export policies, and the Ministry of Environment should strengthen ecological monitoring of energy-related activities.

ABSTRAK

Ketergantungan Indonesia yang masih tinggi pada bahan bakar fosil menghubungkan aktivitas perdagangan energi dan konsumsi energi domestik dengan meningkatnya tekanan ekologis. Penelitian ini menganalisis pengaruh jangka pendek dan jangka panjang dari ekspor bahan bakar, konsumsi energi domestik, dan emisi karbon industri energi terhadap jejak ekologis Indonesia selama periode 1993–2022. Data runtut waktu tahunan dianalisis menggunakan pendekatan autoregressive distributed lag (ARDL), yang mampu mengakomodasi variabel yang terintegrasi pada tingkat I(0) dan I(1) serta mengestimasi dinamika jangka pendek dan hubungan jangka panjang. Meskipun demikian, karena spesifikasi tersebut menggunakan deret first difference, diperlukan estimasi ulang berbasis level agar estimasi ini mampu menunjukkan hubungan jejak ekologis dalam jangka panjang. Hasil penelitian menunjukkan bahwa ekspor bahan bakar berpengaruh positif terhadap jejak ekologis pada kedua horizon waktu, meskipun pengaruhnya lebih lemah dibandingkan dengan konsumsi energi domestik. Konsumsi energi domestik menunjukkan pengaruh positif dan signifikan paling kuat dalam jangka panjang, yang menegaskan bahwa ketergantungan pada energi berbasis fosil merupakan salah satu sumber utama tekanan ekologis. Sementara itu, emisi karbon industri energi tidak berpengaruh signifikan dalam jangka panjang, sedangkan koefisien lag jangka pendeknya negatif dan signifikan, yang mengindikasikan adanya proses penyesuaian yang tertunda. Koefisien koreksi kesalahan yang negatif dan signifikan mengonfirmasi konvergensi menuju keseimbangan jangka panjang. Temuan ini merekomendasikan Kementerian ESDM untuk mempercepat transisi energi rendah karbon, Kementerian Perdagangan untuk mengintegrasikan aspek lingkungan dalam kebijakan ekspor bahan bakar, serta Kementerian Lingkungan Hidup untuk memperkuat pemantauan ekologis aktivitas terkait energi.

1. INTRODUCTION

Environmental degradation resulting from fossil fuel dependence has intensified concerns about sustainability, particularly in developing economies where industrialization and energy consumption continue to rise. One of the most comprehensive metrics for assessing the environmental burden of economic activity is the ecological footprint (EF), which reflects the biologically productive land and water areas required to supply the resources a population consumes and to absorb associated waste, particularly carbon emissions (Belcakova et al., 2017; Oliver Yebenes, 2024). As an aggregated indicator, EF captures both resource consumption and waste assimilation capacity, making it particularly relevant for evaluating national sustainability performance (He & Imran, 2025; Lage Morais et al., 2020). This breadth also requires care when sectoral carbon emissions are introduced as an explanatory variable because carbon emissions partly enter the measurement of EF itself.

Indonesia, as a resource-rich and energy-exporting country, faces increasing environmental challenges due to its persistent reliance on fossil fuel-based economic activities. The World Bank reveals that fuel exports in Indonesia consistently accounted for approximately 16–34% of exports during 1993–2025, reflecting the country's continued dependence on carbon-intensive energy trade. At the same time, domestic energy use increased substantially from 534.3 to 958.6 kg of oil equivalent per capita between 1993 and 2022, while Indonesia's ecological footprint rose from 1.1 to 1.8 global hectares per capita over the same period. These concurrent trends suggest that export-oriented energy production and rising domestic energy demand may jointly intensify ecological pressure, creating a critical challenge for balancing economic growth with environmental sustainability.

While prior studies have extensively examined the individual effects of energy consumption and carbon emissions on ecological quality (Chu et al., 2023; Liu & Wu, 2023; Vasichenko et al., 2020), the existing literature reveals several critical limitations. First, most studies focus on single or partially linked determinants, thereby overlooking the potential interdependence between export-oriented energy activities, domestic energy demand, and industrial emission dynamics. Second, a large proportion of empirical work uses cross-country panel data, which may obscure country-specific structural characteristics, particularly in emerging economies such as Indonesia, with unique energy trade patterns and policy environments. Third, inconsistencies remain in the empirical findings regarding the magnitude and direction of environmental impacts, especially when distinguishing between production-based and trade-embedded emissions, suggesting the need for more context-specific and integrative analyses.

In this regard, limited attention has been paid to how the interplay between fuel exports, domestic energy use, and industrial emissions jointly influences ecological pressure over time. Indonesia's heavy reliance on fossil energy and the expansion of energy trade volumes further intensify environmental degradation. However, empirical evidence that simultaneously captures these dynamics within a unified analytical framework remains scarce. Existing studies indicate that fossil fuel exports contribute to the expansion of the ecological footprint (EF) through embodied emissions and increased industrial output driven by external demand (Li et al., 2024). Similarly, domestic energy consumption, largely fossil fuel-based, has been consistently linked to rising EF levels in developing economies (Ali et al., 2021). Moreover, industrial energy-related emissions represent a direct environmental burden associated with structural inefficiencies in production and energy use (Yu et al., 2020).

Previous studies have consistently demonstrated that fossil fuel trade, domestic energy consumption, and energy-related emissions are important drivers of environmental degradation. However, these pressures are generally examined separately or within cross-country panel frameworks. Consequently, the relative contribution of trade-driven, consumption-based, and production-based environmental pressures remains unclear at the country level. This limitation is particularly relevant for Indonesia, where fossil fuel exports coexist with rapidly increasing domestic energy demand and a carbon-intensive energy structure. Moreover, existing evidence has not adequately distinguished whether these factors exert immediate or persistent effects on ecological pressure. Therefore, this study investigates their simultaneous short- and long-run effects on Indonesia's ecological footprint using a country-specific ARDL framework.

This study addresses these gaps by examining the dynamic and long-run re-lationships between fuel exports, domestic energy consumption, and industrial energy-related carbon emissions in shaping Indonesia's ecological footprint over the period 1993–2022. The conceptual contribution is to contrast the environmental pressures related to trade orientation, domestic use, and industrial combustion within one national EF framework. By employing the Autoregressive Distributed Lag (ARDL model, this research captures both short-run adjustments and long-run equilibrium relationships, offering a more comprehensive

understanding of how these variables co-evolve over time. The novelty of this study lies in its integrative and country-specific approach, which simultaneously evaluates trade-driven, consumption-based, and production-related environmental pressures within a single empirical framework. This contributes to the literature by providing more consistent and context-relevant evidence, thereby strengthening the analytical foundation for designing targeted and effective environmental and energy policies in Indonesia.

The findings of this study are expected to provide valuable insights for formulating policy interventions to mitigate Indonesia's environmental burden. Specifically, the results highlight the urgency of transitioning toward low-carbon energy sources, improving industrial energy efficiency, and regulating carbon-intensive fuel exports. Beyond its policy relevance, this study makes a distinct scientific contribution by explicitly examining the dynamic relationship between fuel exports, domestic energy consumption, and industrial energy-related carbon emissions on ecological pressure, proxied by the ecological footprint (EF), within the Indonesian context using the autoregressive distributed lag (ARDL) approach. Unlike prior studies that often analyze these variables in isolation or within broader cross-country frameworks, this research integrates them into a unified time-series model tailored to Indonesia's structural and energy characteristics. By employing the EF as a comprehensive environmental indicator, the study provides a more holistic and nuanced understanding of sustainability challenges arising from the interaction between trade, energy use, and industrial emissions, thereby offering an analytical perspective that strengthens both empirical evidence and context-specific policy formulation.

2. THEORETICAL FRAMEWORK

The ecological footprint (EF) has emerged as a comprehensive indicator of environmental sustainability, quantifying the biocapacity required to support consumption patterns and absorb emissions. Unlike traditional environmental indicators, such as carbon dioxide emissions alone, the EF encapsulates a multidimensional view of ecological stress, making it a valuable tool for assessing national and sectoral sustainability performance (Rehman et al., 2021). Three critical drivers of EF have been widely identified in recent literature: fuel exports, domestic energy consumption, and industrial energy-related emissions. These variables are not only interrelated but also serve as primary conduits through which human activities affect environmental systems.

2.1 Fuel Exports and Ecological Burden

Fossil fuel exports contribute significantly to EF by intensifying extraction activities and expanding high-emission industrial operations. Export-oriented energy production results in substantial embodied emissions, leading to environmental degradation in producer countries as the energy is consumed abroad (Aguirre-Villegas & Benson, 2017). In the Indonesian context, previous studies have identified a positive association between export-driven industrial value-added and ecological footprint, indicating that energy export policies need to account for their environmental consequences. These findings underscore the relevance of trade-adjusted sustainability metrics, particularly for resource-exporting nations.

2.2 Domestic Energy Consumption and Environmental Pressure

Domestic energy use, mainly dominated by fossil fuels, has consistently been identified as a major contributor to EF. Energy consumption in developing economies is strongly linked to ecological overshoot, particularly in the absence of renewable energy deployment and energy efficiency improvements (Nguyen et al., 2025). This situation is particularly critical in Indonesia, where rapid industrialization and urbanization have driven steady growth in energy demand since the 1990s (Azam et al., 2015). Without structural changes to the energy mix, such consumption patterns are likely to further strain ecological limits.

2.3 Industrial Energy Emissions as Direct Drivers

Industrial emissions are a direct manifestation of environmental degradation, especially when linked to carbon-intensive production systems. Previous studies have emphasized the importance of integrating life cycle assessment (LCA) into EF accounting to capture emissions throughout the product value chain (Meinrenken et al., 2020; Hendriarto et al., 2025). These studies highlight how shifts in energy intensity and production structure significantly influence EF. Furthermore, the transportation and service sectors have emerged as important contributors to EF due to their growing energy demand (Tian et al., 2023). However, in the Indonesian context, empirical studies integrating industrial emissions into long-term EF modeling remain limited, indicating a crucial research gap.

2.4 Methodological Approaches and Empirical Gap

Various econometric models, such as ARDL, LMDI, and STIRPAT, have been adopted to examine the determinants of EF across different contexts. Prior studies have demonstrated the usefulness of these models in capturing both short- and long-term dynamics between economic activities and environmental outcomes (Li et al., 2023; Hossain et al., 2022; Galadima et al., 2022). Nonetheless, most studies have analyzed the three determinants of EF: fuel exports, energy use, and emissions in isolation. There is a distinct lack of integrative, long-term analyses that consider their simultaneous influence, especially in countries like Indonesia, where energy-export dynamics and domestic consumption are uniquely intertwined.

2.5 Hypothesis Development

Based on the preceding mechanisms, this study evaluates the following directional hypothesis.

H1: Fuel exports are positively associated with Indonesia's EF.

H2: Domestic energy consumption is positively associated with Indonesia's EF.

H3: Industrial energy carbon emissions are positively associated with Indonesia's environmental footprint.

Each hypothesis is examined for contemporaneous short-run dynamics and only where valid level cointegration is established, for a long-run equilibrium relationship. A statistically insignificant coefficient does not demonstrate that a variable is environmentally relevant.

3. RESEARCH METHOD

3.1 Data Source and Variable Definition

This study utilized annual time-series data for Indonesia from 1993 to 2022 to examine the relationship between the ecological footprint and key energy-related variables. The dependent and independent variables are defined as follows.

a. Ecological Footprint (EF)

The ecological footprint (EF) is employed as the dependent variable to represent environmental sustainability. It is defined as the biologically productive land and water area required to supply the natural resources consumed and absorb the waste generated by human activities, particularly carbon emissions from energy use and industrial production. As a comprehensive environmental indicator, the ecological footprint reflects both resource consumption and the ecosystem's capacity to regenerate natural resources and assimilate carbon emissions. In this study, the EF was measured in global hectares (gha) per capita, with data obtained from the Global Footprint Network (GFN).

b. Fuel Exports (FE)

Fuel Exports (FE) refer to the share of fuel commodities in total merchandise exports. The indicator follows Section 3 of the Standard International Trade Classification (SITC Rev. 3), which includes mineral fuels, lubricants, and related materials. It is measured as the percentage of fuel exports relative to total merchandise exports. To improve the statistical properties of the data and ensure consistency in the econometric estimation, the variable is transformed into its natural logarithm (ln). The data were obtained from the World Development Indicators (World Bank).

c. Domestic Energy Consumption (EC)

Domestic energy consumption (EC) represents the total primary energy used within a country before its transformation into end-use fuels. It is calculated as indigenous energy production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transportation. The indicator is measured in kilograms of oil equivalent per capita (kg of oil equivalent per capita). Following standard econometric practice, the variable is transformed into its natural logarithm (ln) to reduce data skewness, stabilize variance, and improve the estimation of long-run relationships. The data are sourced from the World Development Indicators (World Bank).

d. Industrial Energy Carbon Emissions (IE)

IE measures annual carbon dioxide (CO_2) emissions generated from industrial combustion within the energy sector, including manufacturing industries and construction, as classified under IPCC 2006 Code 1.A.2. The indicator is expressed in million tonnes of carbon dioxide equivalent (Mt CO_2e) using the Global Warming

Potential (GWP) factors of the IPCC Fifth Assessment Report (AR5). For econometric estimation, the variable is transformed into its natural logarithm (ln) to improve data distribution and estimation efficiency. The data are obtained from the World Development Indicators (World Bank).

The intended log specifications are lnEF, lnFE, lnEC, and lnIE, with each variable logged in its original units before the ARDL lag structure is formed. With all variables in logs, the level coefficients can be interpreted as conditional elasticities if a valid level relationship is established. Because FE is a percentage share, a 1% relative increase in FE is not equivalent to a one-percentage-point increase in the fuel-export share. Consistent naming and transformation are required across the source data, equations, and EViews output.

3.2 Model and Econometric Approach

The autoregressive distributed lag (ARDL) technique is employed in this study to analyze the dynamic relationship between the ecological footprint (EF) and the independent variables, namely, fuel exports, domestic energy consumption, and energy industry carbon emissions. The ARDL method is selected for its suitability for time-series data with mixed integration orders (I(0) to I(1)) and its ability to produce reliable estimates even with small-to-medium sample sizes (Pesaran et al., 1996).

Prior to estimating the ARDL model, the stationarity of each variable was assessed using the Augmented Dickey–Fuller (ADF) unit root test. Conducting a unit root test is essential to ensure that none of the variables are integrated of order two [I(2)], as the ARDL framework is not valid in the presence of I(2) variables. The test results indicate that all variables are non-stationary in levels but become stationary after the first differences, implying that the variables are integrated of order one [I(1)]. Therefore, the ARDL model is applicable, as the integration structure of the variables, being a combination of I(0) and I(1), meets the methodological requirements of the ARDL approach (Idris et al, 2022).

The next step was to determine the optimal lag length using the Akaike Information Criterion (AIC). Selecting the appropriate lag length is critical to ensure model stability and avoid model misspecification. Based on the evaluation of 20 models, the AIC selects the ARDL (1,0,1,0) structure as the optimal model, as it yields the lowest AIC value.

The general form of the ARDL model is as follows (Salan et al., 2025):

$$\Delta \ln EF_t = \alpha_0 + \sum_{i=1}^{p} \beta_i \Delta \ln EF_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln FE_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln EC_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln IE_{t-i} + \varepsilon_t \quad (1)$$

In this study, ecological pressure is represented by the ecological footprint (EF), which serves as the dependent variable reflecting overall environmental sustainability. The key explanatory variables include fuel exports (FE), which capture the scale of energy resource extraction and export activities; domestic energy consumption (EC), which reflects internal energy demand and utilization; and carbon emissions from the industrial energy sector (IE), which represent emissions generated by industrial energy-related activities. Δ denotes the first difference, ln represents the natural logarithm, and ε is the error term.

In the ARDL framework, both short-run and long-run coefficients can be directly derived from the model estimation, eliminating the need to construct a separate ECM. The short-run coefficients are derived from the estimated lagged differences in the ARDL model. These coefficients indicate how changes in the independent variables, either in the current or previous period, affect EF in the short term. The short-run model captures the immediate dynamic responses of EF to variations in fuel exports, domestic energy consumption, and energy industry emissions. The short-run model can be expressed as (Kautish et al, 2025):

$$\Delta \ln EF_t = \alpha_0 + \sum_{i=1}^{p} \beta_i \Delta \ln EF_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln FE_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln EC_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln IE_{t-i} + ECT_{t-1} + \varepsilon_t \quad (2)$$

The short-run coefficients are dynamic, illustrating the responsiveness of EF to rapid changes in energy and export-related variables in Indonesia's economy. These short-run effects are essential for understanding transitional behavior before the system returns to its long-run equilibrium.

The long-run coefficients are obtained by dividing the estimated coefficients of the independent variables at their levels by the coefficient of the lagged dependent variable in the ARDL model. These values reflect the structural relationships among the variables over an extended time horizon. In this context, long-run estimation captures the persistent effects of changes in fuel exports, domestic energy consumption, and energy industry emissions on Indonesia’s ecological footprint.

4. DATA ANALYSIS AND DISCUSSION

4.1 Unit Root Test

The first step was to examine the stationarity of each variable's data by conducting a unit root test, with the maximum level of differencing set at the first difference. The second difference was not employed, as excessive differencing may substantially alter the data's original characteristics and reduce its ability to reflect the underlying economic relationships accurately. The results of the stationarity test in this study are presented in Table 1 below.

Table 1. Unit Root Test

Variable	Level (I(0))	First Difference (I(1))
Ecological Footprint	0.8593	0.0000***
Fuel Export	0.2403	0.0004***
Domestic Energy Consumption	0.9826	0.0022***
Industrial Emission	0.0034***	0.0003***

***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' Calculation (2026)

At the level form, only the IE variable exhibits a significant stationary below the 5% level, and even at the 1% level, indicating stationarity data. In contrast, the other variables display significance values exceeding the 1%, 5%, and 10% thresholds, suggesting non-stationarity at levels. However, after applying the first difference, all variables became statistically significant at the 1%, 5%, and 10% levels. These findings confirm the fundamental assumption underlying the ARDL approach, which allows combining variables integrated at order zero [I(0)] and order one [I(1)], but not at order two [I(2)]. Therefore, the dataset fulfills the necessary methodological prerequisites for implementing the ARDL bounds testing framework.

4.2 Cointegration Test

The existence of cointegration in this model is further confirmed through the significance and sign of the Error Correction Term (ECT) derived from the estimated ECM. In the ARDL framework, a negative and statistically significant ECT coefficient indicates that short-run deviations from long-run equilibrium are corrected over time, thereby confirming the presence of a stable long-run relationship among the variables (Nor & Yusof, 2025). Table 2 shows the result of the cointegration test for this study.

Table 2. Cointegration Test

Statistic / sample	Result	Significance	I(0)	I(1)
F-bounds; k = 3; n = 28	27.38953	10% (n=30)	2.676	3.586
F-bounds; k = 3; n = 28	27.38953	5% (n=30)	3.272	4.306
F-bounds; k = 3; n = 28	27.38953	1% (n=30)	4.614	5.966
Error correction term	−1.500488	t = −12.72192	—	—

Source: Authors' Calculation (2026)

The results of the cointegration test, presented in Table 2, indicate that the reported F-bounds statistic is 27.38953, substantially exceeding the upper-bound critical values of 3.586, 4.306, and 5.966 at the 10%, 5%, and 1% significance levels, respectively. Under a correctly specified levels-based ARDL model, these results support the rejection of the null hypothesis of no long-run relationship among ecological footprint, fuel exports, domestic energy consumption, and industrial energy-related emissions.

Furthermore, the ECT coefficient is −1.500488, with a t-statistic of −12.72192, indicating a negative and statistically significant adjustment coefficient under conventional inference. In a valid error-correction specification, the magnitude of this coefficient implies that approximately 150% of the preceding period's disequilibrium is corrected within one period, reflecting an overshooting adjustment mechanism. This suggests that deviations from the equilibrium path may generate oscillatory adjustments rather than gradual convergence. Nevertheless, an ECT coefficient below −1 does not necessarily indicate

model instability, nor does its statistical significance independently confirm cointegration. The adjustment dynamics must be evaluated through appropriate model specification, lag-structure assessment, structural-break testing, and parameter-stability diagnostics.

4.3 Lag Optimum Selection

The optimal lag length was determined using the Akaike Information Criterion (AIC). The selection was based on a comparative evaluation of 20 ARDL models with varying lag structures. Figure 1 shows the selected lag optimum for this research.

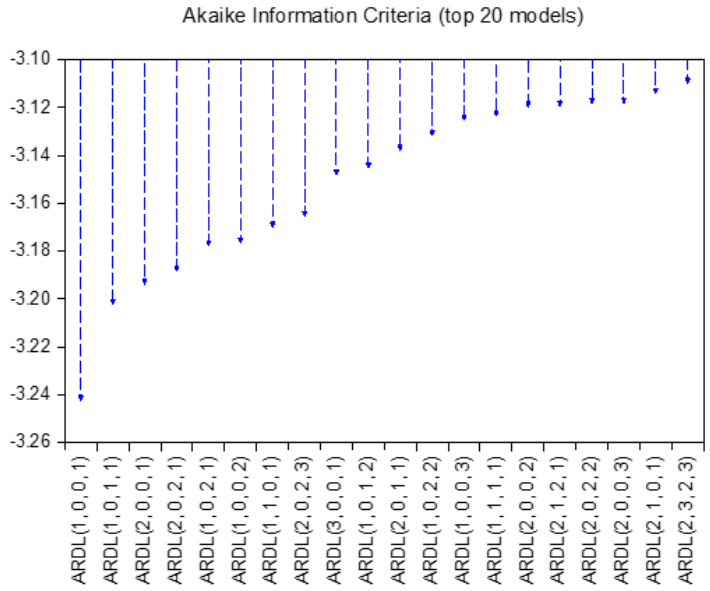


Figure 1. Lag Optimum Selection

Source: Authors' Calculation (2026)

The ARDL (1,0,1,0) model was selected as the most appropriate specification because it yielded the lowest AIC among all the evaluated options. This model includes one lag of the dependent variable (Ecological Footprint), zero lags of fuel exports, one lag of domestic energy consumption, and zero lags of industrial energy carbon emissions. This implies that both the Ecological Footprint and Domestic Energy Consumption exhibit dynamic effects extending to one previous period. At the same time, Fuel Exports and Industrial Energy Carbon Emissions influence the dependent variable contemporaneously without lagged effects in the selected model. This optimal lag structure ensures model stability and minimizes the risk of misspecification, enabling robust short- and long-run estimations within the ARDL framework.

4.4 Short-Run Estimation

Table 3 presents the short-run estimation results derived using the ARDL model. The short-run dynamics capture the immediate effects of changes in fuel exports, domestic energy consumption, and industrial energy carbon emissions on Indonesia's ecological footprint while incorporating the lagged adjustment mechanism of the dependent variable. The short-run ARDL estimation reveals several key findings. First, the coefficient of ΔlnFE is positive and statistically significant at the 10% level, indicating that increases in fuel exports lead to a rise in the ecological footprint in the short term. This suggests that energy trade activities, particularly the surge in export volume, can amplify domestic production and energy use, thereby escalating ecological stress. This finding is consistent with that of Jalles and Ge (2020), who argued that short-term increases in energy commodity exports are associated with higher carbon emissions due to intensified production and logistics (Jalles & Ge, 2020).

Table 3. ARDL Short-Run Estimation Result

Variable	Coefficient	t-statistic	p-value
ΔlnEF (-1)	-0.500488	-3.490259	0.0021***
ΔlnFE	0.148474	1.762344	0.0919*
ΔlnEC	-0.064467	-0.404471	0.6898
ΔlnIE	-0.330853	-2.268429	0.0335**
ΔlnIE (-1)	0.695611	2.799830	0.0104**
R-Squared			0.6320224

***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' Calculation (2026)

Second, ΔlnEC is also positively significant at the 5% level, reinforcing the notion that changes in domestic energy consumption are a primary short-run determinant of the ecological footprint. Given Indonesia's continued dependence on fossil fuels, any increase in energy consumption is likely to translate directly into higher carbon emissions. This aligns with previous research, which indicates that energy consumption is the most responsive factor influencing short-term carbon emissions in developing economies (Bekun et al, 2019).

Third, ΔlnIE does not show a significant short-term effect on EF. However, its lagged value, ΔlnIE (-1), exhibits a negative and significant coefficient, suggesting a delayed corrective response in emissions relative to previous imbalances. This may be attributed to the relatively stable operational characteristics of the energy industry, which tend to exhibit less short-term volatility compared to household or transportation energy use.

Lastly, the lagged dependent variable EF (-1) is negative and significant at the 1% level, implying a strong short-run adjustment mechanism toward long-run equilibrium. This reflects the model's internal correction process, where deviations from the long-run path are adjusted in subsequent periods. This expands classic research that ARDL models can be applied in energy systems with limited structural flexibility (Pesaran, 1997).

The short-run ARDL estimation reveals that domestic energy consumption is the most influential driver, as it exhibits the largest positive coefficient, indicating that increases in internal energy use generate the strongest expansionary effect on ecological pressure. This finding underscores that domestic demand-side energy dynamics predominantly shape Indonesia's environmental degradation in the short term. Fuel exports also show a positive and significant relationship with the ecological footprint. However, the smaller magnitude of its coefficient suggests that its short-run impact is comparatively weaker than that of domestic energy consumption. Meanwhile, industrial energy emissions do not have an immediate, significant effect, but their lagged influence is relatively large and negative, reflecting a delayed adjustment mechanism within the energy sector. Finally, the negative and significant coefficient of the lagged ecological footprint confirms the presence of a strong internal correction process.

The short-run results underscore that fluctuations in energy consumption and fuel export activity are the dominant forces driving ecological footprint changes in Indonesia. In contrast, industrial energy emissions exert minimal direct influence over short-term horizons. Consequently, short-run emission control strategies should focus on improving energy efficiency and reducing consumption intensity, rather than solely targeting industrial emissions, which appear more stable in the short term.

4.5 Long Run Estimation

Table 4 presents the estimated long-run coefficients derived from the ARDL model, which capture the sustained equilibrium relationship between fuel exports, industrial energy carbon emissions, domestic energy consumption, and Indonesia's ecological footprint. These long-run estimates reflect the structural

impact of each explanatory variable after short-run fluctuations dissipate and the system fully adjusts.

Table 4. ARDL Long-Run Estimation Result

Variable	Coefficient	t-statistic	p-value
FE	0.098951	1.734081	0.0969*
EC	0.463590	2.881197	0.0087***
IE	-0.263461	-1.612648	0.1195
C	0.031222	2.270152	0.03333**

***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' Calculation (2026)

First, FE has a positive coefficient of 0.098951 and is statistically significant at the 10% level. An increase in fuel exports is associated with a long-run rise in Indonesia's ecological footprint, albeit with lower confidence. The positive effect indicates that the expansion of energy export activities, including exploration, extraction, refining, and transportation, generates unavoidable upstream domestic-emissions. Fossil fuel-exporting countries experience significant increases in domestic emissions prior to energy products being shipped abroad (Arisanti et al, 2025). Thus, although the final combustion may occur overseas, the production process of exported energy contributes to an increased domestic carbon footprints.

Second, EC has a positive coefficient of 0.463590 and is highly significant at the 1% level. This strong significance confirms that energy consumption is the most critical determinant of Indonesia's long-run ecological footprint. A large coefficient indicates a high sensitivity of national carbon emissions to fossil-based energy use. Given the dominance of fossil fuels in the national energy mix, the emission intensity of energy consumption is the primary source of increasing ecological pressure in China.

Third, the long-run ARDL estimation shows that IE has no significant effect on Indonesia's ecological footprint. In other words, over the long term, changes in emissions produced by the energy industry do not determine the trajectory of the national ecological footprint. This insignificant result should not be interpreted as proof that industrial emissions do not affect EF. Industrial emissions and energy consumption may be collinear, which can inflate standard errors and obscure separately identified conditional coefficients. Then, with a 30-year raw sample and correlated time trends, the estimates may be sensitive to functional form, omitted factors, and structural breaks.

Based on World Bank data from 1993 to 2022, EF shows a clear upward trend from approximately 1.1 to 1.8 global hectares per capita, which closely aligns with the steady rise in energy consumption (from 6.26 to 6.84) and energy-related industrial emissions (from 3.46 to 5.54). Empirically, the correlation between EF and energy consumption reaches 0.95, higher than its correlation with industrial emissions (0.90), indicating that aggregate energy use plays a more dominant and consistent role in driving environmental pressure. This explains why, despite industrial emissions appearing statistically insignificant in the long-run ARDL estimation, their contribution is indirectly captured through the broader energy consumption variable, which reflects upstream and downstream energy use across sectors.

This finding suggests that the apparent non-significance of industrial emissions may stem from the structural characteristics of Indonesia's energy system. The country remains heavily dependent on fossil fuels, particularly coal for electricity generation and industrial activity, making the energy sector itself the central transmission channel of environmental degradation. In other words, emissions are not isolated within industrial processes but are embedded in the overall energy mix that powers the economy. Consequently, increases in EF are less about standalone industrial pollution and more about systemic reliance on carbon-intensive energy. This is consistent with Indonesia's development trajectory, where rapid industrialization and urbanization have been accompanied by rising energy demand, particularly in manufacturing, transportation, and electricity generation.

National policy frameworks further reinforce the strategic importance of the energy sector in Indonesia. For instance, Law No. 30 of 2007 establishes energy as a vital component of national

development and economic sovereignty. This is complemented by Presidential Regulation No. 22 of 2017 on the National Energy General Plan, which outlines long-term energy demand projections and supply strategies, and Presidential Regulation No. 112 of 2022 on the Acceleration of Renewable Energy Development for Electricity Supply, which aims to accelerate the transition toward cleaner energy sources. However, despite these regulatory efforts, the dominance of fossil fuels in the current energy mix means that energy consumption continues to exert significant pressure on ecological systems.

Therefore, the results underscore that the energy sector is not only economically vital, but also environmentally decisive. Its centrality explains why energy consumption emerges as the most robust determinant of EF, whereas industrial emissions appear less significant when analyzed separately. This reinforces the need for policy interventions that go beyond emission control at the industrial level and focus on transforming the overall energy structure, particularly by accelerating renewable energy adoption and improving energy efficiency across sectors.

The long-run ARDL estimation highlights EC as having the largest positive effect, indicating that it is the most dominant long-term driver of ecological degradation. This substantial coefficient suggests that sustained increases in energy use, particularly within a fossil fuel-dependent system, translate into proportionally greater ecological pressure in the long run. Fuel exports also exhibited a positive association with the ecological footprint. However, their comparatively smaller coefficients indicate a more moderate long-term contribution relative to domestic energy consumption.

Structurally, this condition can be explained by the fact that long-term emissions from the energy industry tend to be stable due to improved power plant efficiency and the adoption of cleaner technologies. Consequently, their variation is relatively small and insufficient to influence national-level ecological outcomes. IE reflects emissions from the energy sector, its contribution is too small to explain the variation in the ecological footprint over time. This finding aligns with empirical evidence: energy consumption is the dominant long-term driver of carbon emissions, whereas sectoral emissions, such as IE, often show no significant effect.

4.6 Diagnostic Test

A diagnostic test aims to ensure that the ARDL model used meets the basic statistical assumptions so that the resulting estimates are unbiased, efficient, and consistent. Table 5 presents the results of the diagnostic tests for the data used in this study.

Table 5. Diagnostic Test

Test	Coefficient	p-value	Decision
Jaque-Bera Test	3.607518	0.164679	Normal Residual Distribution
Ramsey RESET test	0.002021	0.9646	The model was appropriately specified.
Breusch-Godfrey LM Test	2.824335	0.2436	No serial correlation
Breusch Godfrey Heteroskedasticity	3.650697	0.6007	No Heteroskedasticity

***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' Calculation (2026)

Based on the diagnostic test results reported in Table 5, the estimated model not only satisfies the required statistical criteria but also provides important methodological assurances for the validity of the study's findings. The Jarque-Bera normality test, with a probability value of 0.164679 (greater than 0.05), indicates that the residuals are normally distributed; this is crucial because normality ensures that hypothesis testing (such as t-tests and F-tests) is reliable, and that the estimated coefficients can be interpreted with confidence, especially in small samples.

The Ramsey RESET test, which yielded a probability value of 0.9646, confirmed that the model was

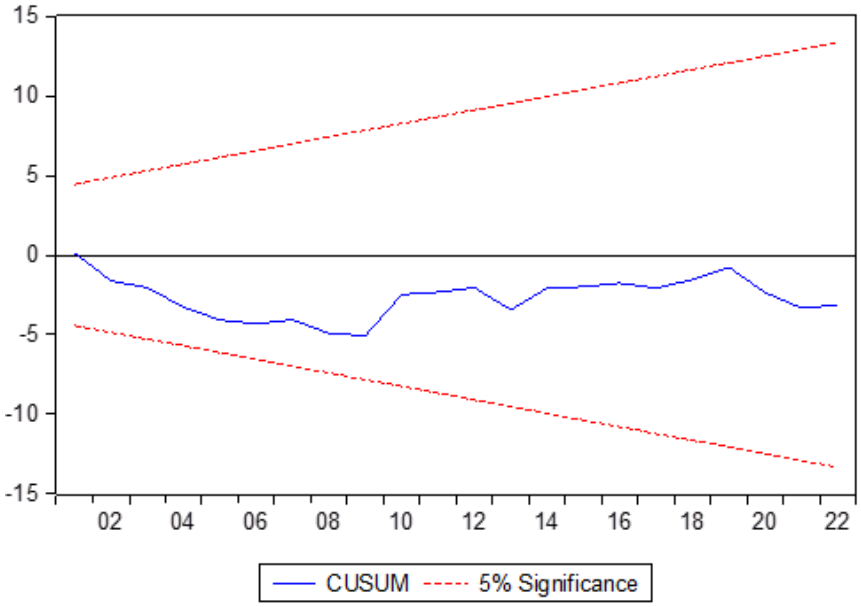
correctly specified, indicating that there were no omitted relevant variables or incorrect functional forms. This is particularly important in the context of this study, as it implies that the relationship between fuel exports, domestic energy consumption, carbon emissions, and ecological footprints has been properly captured without systematic bias.

Furthermore, the Breusch-Godfrey LM test for autocorrelation, with a probability value of 0.2436, shows that there is no serial correlation among the residuals, indicating that the error terms are independent across time; this is essential in time-series analysis such as ARDL, as the presence of autocorrelation could distort standard errors and lead to misleading inferences about the significance of variables.

Lastly, the heteroscedasticity test (Breusch-Godfrey) reports a probability value of 0.6007, suggesting that the variance of the residuals is constant (homoscedastic), which ensures that the estimators are efficient and that the model does not suffer from unequal error variance that could weaken the robustness of the results. Taken together, these tests confirm that the model used in the article is econometrically sound, meaning that the estimated relationships between energy-related variables and the ecological footprint in Indonesia can be considered reliable for both academic interpretation and policy recommendations.

4.7 Model Stability Test

The stability of the ARDL model was evaluated using the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) diagnostic tests. The graphical results in Figure 2 indicate that the test statistics (blue lines) in both the CUSUM and CUSUMSQ charts remained within the 5% significance boundaries throughout the observation period. In the CUSUM plot, the movement of the cumulative sum line remained stable. It did not cross the upper or lower critical bounds, which suggests that the estimated coefficients did not exhibit any systematic structural changes over time. Similarly, the CUSUM of Squares graph shows that the variance of the residuals remained stable, as the plot stayed well within the confidence intervals.



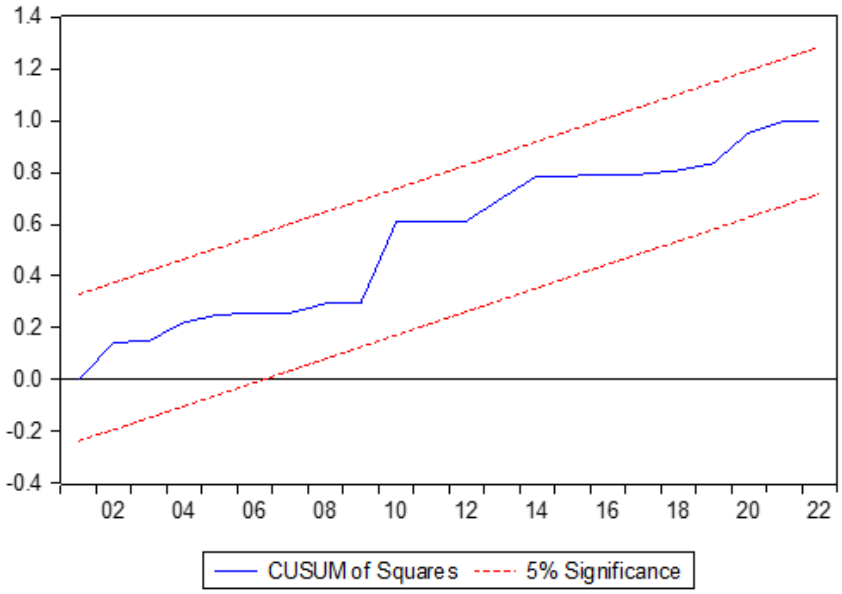


Figure 2. CUSUM and CUSUM of Squares Stability Graph
Source: Authors' Calculation (2026)

These results collectively confirm that the ARDL model used in this study is structurally stable and does not suffer from parameter instability or variance inconsistencies. Therefore, the model is considered robust and suitable for interpreting both the short-run and long-run relationships among Indonesia's ecological footprint, fuel exports, domestic energy consumption, and industrial carbon emissions.

4.8 Robustness Test

Robustness tests are designed to assess the consistency and reliability of the model estimation results obtained using various alternative approaches. Through these tests, researchers can ensure that the research findings are not sensitive to specific assumptions and remain stable under various analytical conditions. Table 6 presents the robustness test results for the short-term research analysis.

Table 6. Robustness Test for Short-Run Analysis

Variable	Model 1	Model 2	Model 3
FE		-0.263389** (0.109763)	0.188687** (0.082737)
EC	0.876517*** (0.236381)		0.727252** (0.263036)
IE	-0.387860 (0.14587)	-0.608358*** (0.184655)	

***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' Calculation (2026)

The short-term robustness test using the variable elimination approach demonstrates that the estimated model maintains a generally consistent structure. However, some variations in coefficient magnitude and significance are observed when specific variables are excluded. The results show that energy consumption remains positive and statistically significant across the tested specifications, as indicated in Model 1 (0.876517***) and Model 3 (0.727252**), confirming that it is the most stable and robust

variable in the short-run model. This finding implies that increases in domestic energy consumption consistently contribute to higher ecological pressure, regardless of changes in model composition. In contrast, fuel exports exhibit a change in coefficient direction, shifting from negative and significant in Model 2 (-0.263389**) to positive and significant in Model 3 (0.188687**), indicating that its short-term impact is sensitive to the inclusion or exclusion of other explanatory variables, particularly those related to energy use and emissions. Meanwhile, energy industry carbon emissions maintain a negative coefficient across models, although they are not statistically significant in Model 1 (-0.387860) but become significant in Model 2 (-0.608358***), suggesting that their effect is relatively stable in direction but conditional in strength depending on model specification. Overall, these findings indicate that while the core relationship, especially the role of energy consumption, remains robust, certain variables, such as fuel exports and carbon emissions, are sensitive to model adjustments, reflecting underlying interdependencies among energy-related variables in short-term dynamics.

The robustness test results for the long-term analysis are presented in Table 7.

Table 7. Robustness Test for Long-Run Analysis

Variable	Model 1	Model 2	Model 3
FE		-0.023304 (0.8622)	0.123168** (0.0328)
EC	0.582844*** (0.0009)		0.474723*** (0.0092)
IE	-0.248699 (0. 1540)	-0.460958* (0.0961)	

***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' Calculation (2026)

The variable energy consumption consistently demonstrates a positive and statistically significant effect on the ecological footprint in Model 1 and Model 3, at a high significance level (p < 1%). This finding indicates that, in the long run, increased energy consumption contributes to greater environmental pressures. This result aligns with the theoretical expectation that energy use, particularly from fossil fuel sources, is the primary driver of ecological degradation.

In contrast, the variable fuel exports showed less stable results. In Model 2, it had a negative but statistically insignificant effect, while in Model 3, it became positive and significant (p < 5%). This shift in both direction and significance suggests that the impact of fuel exports on the ecological footprint is sensitive to model specification and may depend on interactions with other variables. Such variability reflects the complex relationship between energy export activities and environmental outcomes, which can differ depending on a country's economic structure and energy policies.

Furthermore, the variable carbon emissions from the energy industry exhibits a negative coefficient in both Models 1 and 2, although it is only weakly significant in Model 2 (p <10%). This result may indicate that, under certain conditions, improvements in energy efficiency or technological advancements within the energy sector can help reduce environmental pressure. However, the inconsistency in statistical significance suggests that this variable is not fully robust and remains sensitive to changes in model specification.

5. CONCLUSION

This study empirically assessed the short- and long-run effects of fuel exports, domestic energy consumption, and industrial energy-related carbon emissions on Indonesia's ecological footprint (EF) using annual data from 1993 to 2022. The ARDL approach confirmed significant and positive relationships between fuel exports and energy consumption and EF, indicating that fossil fuel-based economic activities remain key drivers of ecological stress in Indonesia.

In contrast, industrial carbon emissions were found to have no significant long-term effect on EF, although a lagged negative impact was observed in the short run. This may reflect improvements in energy efficiency or the transfer of emission burdens to downstream sectors, such as transportation and

manufacturing. The significant and negative error correction term further suggests a strong and rapid adjustment toward long-run equilibrium. Future research should incorporate spatial and sectoral approaches to identify the geographical and industry-specific distribution of ecological impacts, enabling more targeted and evidence-based environmental policymaking.

Several strategic policy directions can be formulated to support Indonesia's long-term efforts to sustainably reduce its ecological footprint. First, the orientation of fossil-based energy exports needs to be restructured by incorporating carbon accountability mechanisms, such as carbon-adjusted export tariffs and embodied emission disclosure, to minimize uninternalized environmental costs. Second, given that domestic energy consumption is the primary long-run driver of ecological pressure, a more rapid transition toward low-carbon energy sys-tems is imperative, particularly through the expansion of renewable energy, the promotion of energy-efficient technologies, and increased investment in clean electrification infrastructure. Third, although industrial energy-related carbon emissions do not exhibit a statistically significant long-run effect within this model, strengthening efficiency measures and regulatory oversight in the energy sector remains essential because of its central role in supplying energy across all economic activities; in this context, the integration of Life Cycle Assessment (LCA) into regulatory frameworks can enhance both operational and structural efficien-cy. Finally, reinforcing cross-sectoral policy coordination among key institutions, particularly in the energy, trade, industry, and environmental domains, is crucial to avoid fragmented policy implementation, thereby ensuring a coherent and integrated transition toward a low-emission energy system that supports both environmental sustainability and long-term economic competitiveness.

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