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Dynamic Effects of Energy Transition and Financial Development on Carbon Productivity: Empirical Evidence from Indonesia

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Abstract

Research Originality: This study offers a new perspective on carbon productivity in Indonesia, exploring how energy transition and financial development influence carbon productivity in the short and long term. It provides valuable insights into the mechanisms driving a low-carbon economy, a topic which the existing literature does not fully cover.

Research Objectives: This study aims to determine the dynamic effects of energy transition and financial development on carbon productivity.

Research Method: An error-correction mechanism (ECM) was employed, using Indonesian data from 1982 to 2024. The selection of ECM was predicated on its demonstrated aptitude to discern the temporal dynamics of variables, both in the immediate and extended periods.

Empirical Results: The results show that energy efficiency and renewable energy use improve carbon productivity. Financial development also has a positive effect, although its magnitude is modest. Energy efficiency is the most influential variable. Additional variables show that natural resource rent has a positive effect, while globalization is statistically insignificant. The error-correction term is negative and significant, confirming convergence toward a long-run equilibrium.

Implications: The government must strengthen energy-efficiency policy, accelerate renewable energy deployment, expand green-oriented finance, and allocate natural resource revenues towards sustainable infrastructure and low-carbon investment. These measures support Indonesia's development and net-zero transition.

Keywords:
low-carbon efficiency; energy efficiency; renewable energy; financial deepening; error correction mechanism

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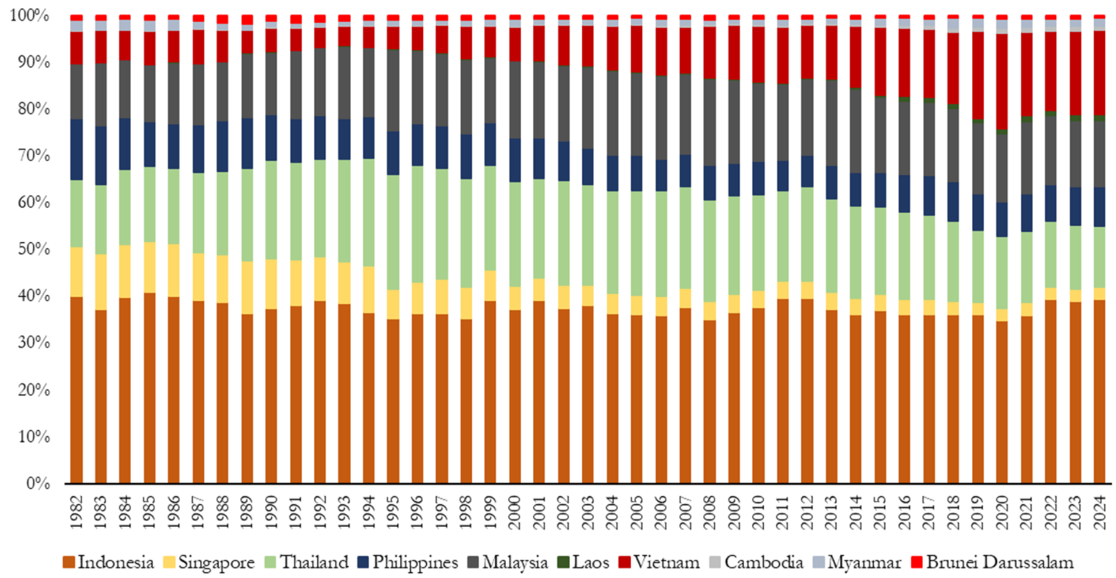
INTRODUCTION

Climate change is a major challenge to sustainable development. In addition to ecological degradation, it affects human well-being, economic stability, energy security, and long-term development prospects (Shen et al., 2021). Past literature has reported that carbon emissions drive climate change (Liu & Bae, 2018; Li & Wang, 2019). Global carbon emissions have risen 13 percent over the past decade, with the energy sector being the largest contributor (Wiloso et al., 2024). This rise is mostly due to the carbon-intensive production and energy systems that many countries rely on for their economic activities. Consequently, numerous countries, including Indonesia, have committed to reducing emissions and achieving the goals outlined in the Paris Agreement (UNFCCC, 2022). The fundamental challenge is determining methods to reduce emissions without sacrificing economic growth.

This issue is especially important in Indonesia. The country is currently the tenth-largest carbon emitter worldwide and the largest in the Association of Southeast Asian Nations (ASEAN) (Wiloso et al., 2024). As shown in Figure 1, Indonesia has always been the biggest ASEAN carbon emitter since 1982. In the early 1980s, the country was already contributing 40 percent of ASEAN's total emissions, and in recent years it has been 35-39 percent. This contribution is significantly higher than that of its neighboring countries, such as Singapore, Brunei, the Philippines, and Malaysia. Therefore, as the largest carbon emitter in ASEAN and globally, any progress or failures in its efforts to reduce carbon emissions will have a significant effect on regional and global environmental performance.

Figure 1. Shares of Carbon Emissions in ASEAN (Percent) 1982-2024



At the same time, Indonesia faces a structural dilemma. The country must maintain economic growth to support industrialization, job creation, poverty alleviation, and

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increased energy demand. However, periods of economic expansion have always been accompanied by mounting environmental pressures and increased emissions. Figure 2 shows Indonesia's carbon and economic growth between 1982 and 2024. During this period, economic growth has remained relatively stable, between 4 and 7 percent, apart from periods of major crisis.

In contrast, carbon emissions have been much more volatile, ranging from negative to almost 20 percent in certain years. Both variables experienced sharp contractions during the 1998 Asian financial crisis and the 2020 COVID-19 period, when economic growth declined, and carbon emissions also fell. Since then, economic growth has gradually returned to the positive territory, while carbon emissions have continued to fluctuate erratically. Therefore, Indonesia needs a strategy that both supports development and improves the environment. The government has promised to peak carbon emissions by 2030 and reach carbon neutrality by 2060 (Ministry of Environment and Forestry, 2021). However, these targets cannot be achieved solely through conventional emission-reduction policies; they also need a low-carbon economy that balances growth and carbon reduction. The challenge is that while high-carbon growth is unsustainable, low-carbon policies without sufficient economic progress may be difficult to sustain politically and socially (Wu & Yao, 2023). In this context, carbon productivity may be a viable option for guiding the appropriate course of action (Cheng & Yao, 2021; Sun et al., 2021).

Figure 2. Carbon Emissions and Economic Growth in Indonesia (Percent) 1982-2024

The concept of "carbon productivity" refers to the amount of output achieved per unit of carbon and is essential for evaluating low-carbon economic growth. Typically, strong economic and social development is accompanied by high carbon productivity (Cui et al., 2023). Therefore, measuring carbon productivity is important for achieving low-carbon economic growth, as it holds governments accountable for tackling climate change, informs low-carbon policies, and identifies sustainable economic development priorities (Du et al., 2022). Thus, enhancing carbon productivity is key for Indonesia and requires urgent research.

Several factors influence carbon productivity, including energy transition policies. These policies support the shift towards a low-carbon economy by promoting a more sustainable, efficient, competitive, and secure energy system. Such policies also target energy consumption, as it is the main source of emissions (Saraji & Streimikiene, 2023). Meanwhile, increasing renewable energy and efficiency are effective strategies for energy transition. Together, these can achieve up to 90 percent of the emissions reductions needed for net zero (IRENA, 2021). In principle, both should enhance carbon productivity by reducing dependence on fossil fuels, lowering emissions, and enabling greater output with lower carbon intensity. However, the transition to cleaner energy systems often requires substantial investment, technological adaptation, institutional readiness, and infrastructure restructuring, which may weaken its benefits in the short run, particularly in developing countries where fossil fuels still dominate. As a result, the effects of renewable energy and energy efficiency on carbon productivity may differ between the short- and long-run. Hence, the academic debate is not only about whether the energy transition matters, but also about how, through what mechanisms, and over what time horizon it affects carbon productivity. This issue is especially relevant in Indonesia, where the economy remains heavily reliant on fossil fuels despite the setting of ambitious decarbonization targets.

The development of the financial sector is another key factor in determining carbon productivity. This development refers to the measures a country takes to promote financial activities, including capital markets, banking, and domestic and foreign investment. A more advanced financial system can influence carbon productivity by enhancing the mobilization and allocation of capital (Zafar et al., 2019). Improved access to financing can lead to investment in environmentally friendly technologies, the modernization of production processes, and more efficient resource use, thereby increasing output while reducing carbon emissions. However, financial sector development can also increase credit availability for carbon-intensive and energy-wasting production activities, thereby increasing emissions (Byaro et al., 2024). Therefore, its impact on low-carbon development is not always positive, as it depends on how financial resources are channeled within the economy. Research findings are divided into two categories; some studies find a positive relationship (Yuan et al., 2019; Khan & Ozturk, 2021), while others report a negative relationship (Khan et al., 2022; Sai et al., 2023). This issue is particularly interesting to study for Indonesia, where financial deepening continues alongside the need for a low-carbon economy.

Despite the valuable insights from previous studies, important knowledge gaps remain in the literature. Firstly, the effects of renewable energy consumption, energy efficiency, and financial development on carbon productivity remain inconclusive. Moreover, much of the literature relies on static approaches (Khan et al., 2022; Meng et al., 2022; Huang

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et al., 2023), while studies using dynamic models generally focus only on the existence of relationships rather than explicitly distinguishing short- and long-run effects, even though the impacts of energy transition and financial development are inherently dynamic (Cheng & Yao, 2021; Murshed et al., 2022). Thirdly, empirical evidence for Indonesia remains limited, as previous studies tend to focus either on emissions or on economic growth separately, without integrating both through the concept of carbon productivity (Elfaki et al., 2021; Tiawon & Miar, 2023). This issue is particularly important because Indonesia must reduce emissions while maintaining economic development. Therefore, this study adopts a dynamic approach to examine the short- and long-run effects of renewable energy consumption, energy efficiency, and financial development on carbon productivity in Indonesia. It aims to clarify the roles of renewable energy consumption and energy efficiency as the core dimensions of energy transition, while also identifying how financial development shapes carbon productivity over time. The novelty of this study lies in its integrated, dynamic analysis of the relationships among energy transition, financial development, and carbon productivity in the Indonesian context. In addition, the findings are relevant to achieving Sustainable Development Goals 7, 8, 9, and 13, and they offer academic and policy insights into low-carbon development in Indonesia.

METHODS

This study used secondary time-series data from Indonesia, covering 43 years from 1982 to 2024. This period was selected to capture the integration of environmental considerations into national development since the enactment of the first environmental law in 1982. The researchers sourced the data from the World Bank, Our World in Data, and the KOF Swiss Economic Institute. The dependent variable is carbon productivity, which can be measured as single-factor or total-factor carbon productivity (Wang et al., 2019; Wu et al., 2021). Single-factor measures have been widely used (Hu & Liu, 2016; Guo et al., 2021) and are methodologically reliable (Meng et al., 2022). The independent variables in this study are financial development, energy intensity (a proxy for energy efficiency), and renewable energy consumption. Meanwhile, the present study also incorporates the concept of natural resource rent (Chen et al., 2023) and globalization (Jahanger et al., 2022). The utilization of natural resources plays an instrumental role as a primary driver of economic advancement, exerting an indirect influence on environmental quality (Li et al., 2023). Globalization also has the potential to facilitate carbon reduction by increasing the global movement of production factors, driving innovation and technology exchange, and encouraging international cooperation (Yuping et al., 2021). Table 1 provides a detailed explanation.

The Error Correction Mechanism (ECM) is a time-series model used to analyze the cointegrated relationship between dependent and independent variables in the present and the past (Engle & Granger, 1987). The model corrects short-term imbalances toward long-term equilibrium and can also address spurious regression by using the first-difference formulation. These characteristics make ECM an appropriate model for achieving the objectives of this study. These objectives include identifying the impact of financial development, energy efficiency, renewable energy use, natural resource rents, and globalization on carbon productivity, and distinguishing whether these effects occur in the short or long term.

Table 1. Details of the Research Variables

Variable	Definition	Unit	Source
Carbon Productivity (CP)	The ratio of PPP GDP (in constant 2011 US dollars) to total CO_2 emissions (from industrial activity and energy use)	USD/Tonnes	Manual calculation based on relevant data from Our World in Data and World Bank
Financial Development (Findev)	The ratio of bank loans or financing to the private sector relative to GDP	Per cent (%GDP)	World Bank
Energy efficiency (EF)	The ratio of total primary energy consumption to PPP GDP	kWh/USD	Our World in Data
Renewable energy use (Ren)	Amount of primary renewable energy consumption	Terawatt-hour (TWh)	Our World in Data
Natural resource rent (NRR)	The ratio between the sum of oil rent, natural gas rent, coal rent, mineral rent, and forest rent to GDP	Per cent (%GDP)	World Bank
Globalisation (Glob)	An index for the examination of globalization in the economic, political, and social spheres	Point	KOF Swiss Economic Institute

This empirical model is derived from the production function approach. Carbon productivity reflects the efficiency with which economic output is generated per unit of carbon emissions. It is closely linked to the production process. Changes in renewable energy consumption, energy efficiency, financial developments, and supportive macroeconomic conditions can alter an economy's ability to generate higher output with lower carbon emissions. Therefore, the Cobb-Douglas form is widely used for such analyses as it links carbon productivity to productive inputs and structural factors that influence production efficiency. The general functional relationship in this study can thus be expressed as follows:

$$\mathrm{CP_t} = \mathrm{f(Findev_t, EF_t, Ren_t, NRR_t, Glob_t)} \quad (1)$$

Using ECM, a derivative of the Ordinary Least Squares (OLS) regression model, divides the equation of the cointegrated variables into two equations, namely the long run and the short run. Thus, Equation 1 can be formed into a log-linear regression based on the Cobb-Douglas function. The long-run model is written as follows:

$$\ln(\mathrm{CP_t}) = \beta_0 + \beta_1 \mathrm{Findev_t} + \beta_2 \ln(\mathrm{EF_t}) + \beta_3 \ln(\mathrm{Ren_t}) + \beta_4 \mathrm{NRR_t} + \beta_5 \ln(\mathrm{Glob_t}) + \varepsilon_t \quad (2)$$

where ln denotes the natural logarithm, β_0 is the intercept, β_1 to β_5 are the long-run parameters to be estimated, and ε_t is the error-term. The logarithmic transformation is used for three main reasons. Firstly, scale differences among variables are reduced. Secondly, variance is stabilised, and potential heteroskedasticity is mitigated. Thirdly, each slope coefficient is interpreted as an elasticity, showing the per centage change in

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carbon productivity associated with a one-per cent change in each explanatory variable, ceteris paribus. Meanwhile, the equation of the short-term model is as follows.

$$\Delta \ln(CP_t) = \gamma_0 + \gamma_1 \Delta Findev_t + \gamma_2 \Delta \ln(EF_t) + \gamma_3 \Delta \ln(Ren_t) + \gamma_4 \Delta NRR_t + \gamma_5 \Delta \ln(Glob_t) + \vartheta \widehat{\varepsilon_{t-1}} + v_t \quad (3)$$

where Δ denotes the first-difference operator, β_0 is the intercept of the short-run model, γ_1 to γ_5 are the short-run parameters to be estimated, $\widehat{\varepsilon_{t-1}}$ is the lag residual of the long-run model or called the error correction term (ECT), and v_t is the error term of the short-run model. In this equation, all explanatory variables are expressed in first differences, meaning that the coefficients measure the immediate or short-run effects of changes in each variable on changes in carbon productivity. In addition, the inclusion of an error-correction term is key to the ECM, as it links short-term dynamics to long-term equilibrium relationships. The error-correction term coefficient (ϑ) is expected to be negative, with an estimate between 0 and -1, and statistical significance. The negative sign indicates that short-term imbalances will be corrected over time, while the magnitude of the value reflects the speed of the adjustment. The larger the absolute value of ϑ, the faster the system returns to its long-run equilibrium path.

RESULTS AND DISCUSSION

The primary empirical results of the econometric modeling revealed three key findings. Firstly, all variables are non-stationary at their original levels but become stationary after first-order differentiation, thereby confirming the hypothesis that these variables are cointegrated of the same order. Secondly, a residual-based cointegration test confirmed the stable long-run equilibrium relationship among carbon productivity, financial development, energy intensity, renewable energy usage, natural resource rents, and globalization. Thirdly, the estimated coefficients consistently indicate that financial development, renewable energy consumption, and natural resource rents increase carbon productivity, whereas energy intensity reduces it. In contrast, the impact of globalization in both the long and short term is not statistically significant. These findings indicate that Indonesia's carbon productivity is predominantly influenced by domestic factors related to finance and energy, rather than by globalization.

Figure 3 illustrates the significant variability in the level and growth of carbon productivity in Indonesia between 1982 and 2024. This variability indicates that Indonesia's low-carbon economic performance has not yet stabilized. The lowest carbon productivity was recorded in 1999 at 3696.942 USD per tonne, while the highest was recorded in 2024 at 5616.005 USD per tonne. This pattern suggests that Indonesia's output per unit of carbon emissions remains highly sensitive to structural economic changes, energy-use patterns, and macroeconomic shocks. The alternating periods of decline and recovery reflect ongoing challenges in sustaining economic growth while improving environmental efficiency. This phenomenon is common in developing countries, which experience recurrent phases of growth in terms of carbon emissions (Calvia, 2024).

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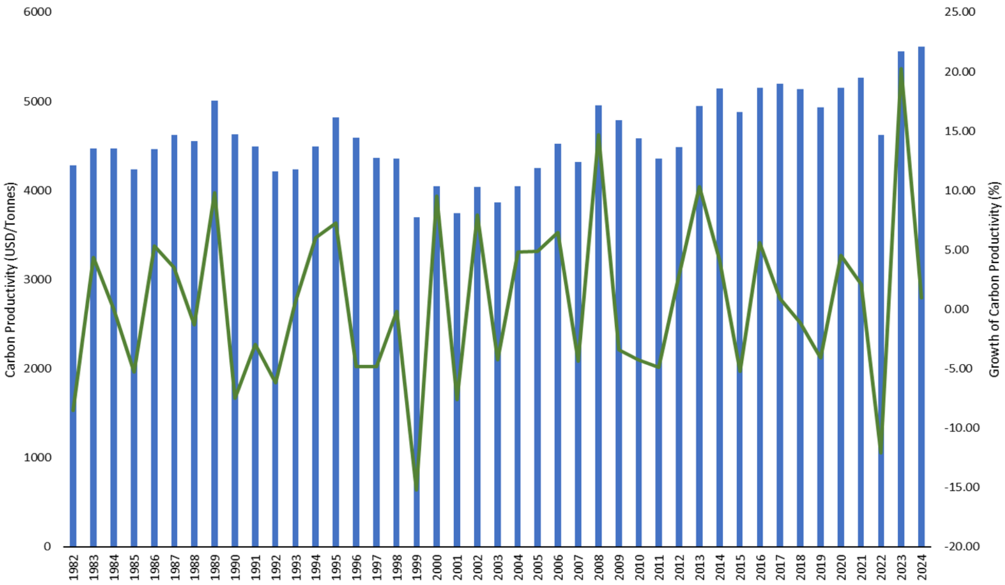
Figure 3. Indonesia's Carbon Productivity and Growth Rate (Percent) 1982-2024



Before initiating the modeling process, a series of stationarity tests was conducted for each variable using the Augmented Dickey-Fuller (ADF) test. The ADF test is a straightforward, widely used, and more effective stationarity test than other available options. The results of these tests are presented in Table 2. As demonstrated in the table, none of the variables are stationary at level or I(0). Consequently, the test was H_0ntinued at the first difference, or I(1), resulting in the rejection of the null hypothesis ( ) for each variable at the 5 percent significance level. Therefore, all variables are stationary at that level.

Table 2. Unit Root Test

Variable	Intercept		Intercept & Trend	
	Level	First Diff	Level	First Diff
ln(CP)	-1.956 (0.304)	-8.921*** (0.000)	-2.662 (0.257)	-8.957*** (0.000)
Findev	-2.593 (0.103)	-4.604*** (0.001)	-2.637 (0.267)	-4.599*** (0.004)
ln(EF)	-0.887 (0.783)	-6.689*** (0.000)	-1.576 (0.786)	-7.070*** (0.000)
ln(Ren)	-1.094 (0.709)	-8.067*** (0.000)	-3.030 (0.137)	-7.999** (0.000)
NRR	-1.975 (0.296)	-9.057*** (0.000)	-3.520* (0.050)	-8.945*** (0.000)
ln(Glob)	-2.591 (0.103)	-4.997*** (0.000)	-0.786 (0.959)	-5.481*** (0.000)

Note: the sign () indicates the p-value. * Significant at 10%, ** Significant at 5%, and *** Significant at 1%

The subsequent step was to estimate the regression model with variable-level values (Long-Term Model) (Table 3). However, even if all variables are stationary at the same level, a cointegration relationship may still exist. Hence, cointegration testing was

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conducted. Table 4 shows that the test rejects the null of the stationary residual series, indicating that the residual series is stationary or, implicitly, that there is a cointegration relationship between the variables.

Once the cointegration relationship has been identified, the long-run model can be interpreted with a reasonable degree of confidence. The results of the simultaneous test (F-test) are presented in Table 3 show that at least one independent variable has a significant impact on carbon productivity in the long run. Moreover, the adjusted R-squared value of 0.825 indicates that the long-term model of carbon productivity can be explained by all independent variables to the extent of 82.5 percent, with the remaining portion explained by variables outside the model. At the partial level, all independent variables of the model have a significant long-run effect on carbon productivity, except for globalization. This pattern indicates that Indonesia's carbon productivity is influenced predominantly by domestic structural factors, particularly those related to finance, energy use, and resource management, rather than by external integration alone.

The following section addresses the immediate-term impact of the five research variables. However, before examining the outcomes of the short-term modeling, it is imperative to ensure that the fundamental tenets of OLS modeling are not violated, thereby ensuring that the parameters generated represent the most precise and unbiased estimator. Table 5 presents the results of the test for the classical assumptions on the short-term model. All classical assumptions are met when the residuals of the short-term model are normally distributed, homoscedastic, and uncorrelated over time. In addition, the independent variables are uncorrelated, and there is no evidence of multicollinearity.

Table 3. Estimation of the Long- and Short-Term Model of Carbon Productivity

Variable	Long-Term Model		Short-Term Model	
	Coefficient	Std.Error	Coefficient	Std.Error
Constant	7.771^{***} (0.000)	0.404	-0.001 (0.875)	0.007
Findev	0.001^{*} (0.053)	0.001	0.002^{**} (0.025)	0.001
ln(EF)	-0.647^{***} (0,000)	0.075	-0.849^{***} (0.0000)	0.114
ln(Ren)	0.039^{**} (0.023)	0.016	0.065^{*} (0,099)	0.039
NRR	0.012^{***} (0.005)	0.004	0.011^{***} (0.0012)	0.003
ln(Glob)	0.063 (0.559)	0.107	-0.139 (0.592)	0.256
$\widehat{\varepsilon_{t-1}}$	-	-	-0.749^{***} (0.000)	0.153
F-Statistic	40.571^{***} (0.0000)		18.683^{***} (0.000)	
R-squared	0.846		0.762	
Adj R-squared	0.825		0.721	
Durbin-Watson	1.474		2.122	

Note: the sign () indicates the p-value. *10%, **5%, and ***1%

Table 3 presents the estimates from the short-term carbon productivity model. The simultaneous rejection of the test decision indicates that one or more independent variables significantly influence short-term carbon productivity. At the same time, the adjusted R-squared of 0.721 indicates that 72.1 per cent of the diversity in the short-term carbon productivity model in Indonesia can be explained by all independent variables, with the remaining 27.9 per cent explained by variables not included in the model. Additionally, only globalisation had no significant effect on carbon productivity in the short term. Meanwhile, financial development, energy efficiency, renewable energy consumption, and natural resource rents all had significant effects on short-term carbon productivity. The four significant variables show a similar relationship to the long-term model estimates, validating the reliability of the independent variables and enhancing the interpretability of the results.

The development of the financial sector has a positive impact on carbon productivity in Indonesia over time. These findings suggest that the expansion of the financial sector has supported more efficient economic activity patterns, rather than merely driving output growth without considering its environmental consequences. In the short term, increased financial intermediation can facilitate companies' access to credit, enabling them to upgrade equipment, adopt more efficient production processes, and improve operational performance (Le et al., 2020; Khan & Ozturk, 2021). These adjustments can boost productivity while limiting the growth of carbon pressures associated with current production. In the long term, this positive relationship indicates that financial development also contributes to broader structural changes by facilitating the allocation of capital to more productive sectors, driving technological advancement, improving the quality of the workforce, and expanding investment capacity in economic activities with lower carbon intensity (Yuan et al., 2019; Sai et al., 2023).

Table 4. Cointegration test

Variable	Intercept	Intercept & Trend
$\widehat{\varepsilon_{t-1}}$	-4.893***	-4.832***
(ECT)	(0.000)	(0.002)

Note: the sign () indicates the p-value. *10%, **5%, and ***1%

This interpretation is also reinforced by more recent evidence showing that green finance and digital financial inclusion can enhance carbon productivity through green innovation, industrial upgrading, and cleaner resource allocation (Li et al., 2024; Lei et al., 2025). These findings are highly relevant in the Indonesian context, where financial development continues amid the challenge of sustaining growth while implementing a low-carbon development agenda. As a developing country with rising energy demand, Indonesia needs a financial system that both mobilizes capital and drives productive, efficient, and increasingly environmentally friendly activities. The positive significance of these financial developments aligns with Li et al. (2025) and Mwita et al. (2025) and indicates that Indonesia's financial sector has begun to play a constructive role

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in supporting economic modernization without proportionally increasing the carbon burden. At the same time, the relatively small scale of this impact suggests that this role remains limited and may not yet fully reflect a strong commitment to green finance. Therefore, the benefits of financial development for carbon productivity could be further strengthened if financial policies were more explicitly aligned with energy transition goals, particularly through greater support for cleaner technologies, efficient infrastructure, and environmentally oriented investments.

Table 5. Classical Assumptions Test

Problem	Test	Statistics	Prob
Serial Correlation	Breusch-Godfrey LM Test	0.469	0.630
Heteroscedasticity	Breusch-Pagan Test	0.990	0.447
Normality	Jarque-Berra test	1.432	0.489
Multicollinearity	Variance Inflation Factor (VIF)	1.169 (mean)	-

The statistical analysis also indicates that energy efficiency significantly improves carbon productivity. This effect is observed in both the short- and long-term. It is consistent with expectations, demonstrating the absence of an energy rebound effect (where an increase in energy efficiency is expected to reduce total energy consumption, only to be followed by an increase in energy consumption). Given Indonesia's reliance on fossil fuels, increased energy efficiency will reduce total energy consumption, prevent energy waste in economic activities, and is a step towards addressing climate change from the energy demand side (Trotta, 2020). Moreover, improving energy efficiency can increase carbon productivity by efficiently reducing energy consumption as a factor of production without compromising overall energy demand. Recent studies have also shown that stronger corporate energy management, which focuses on reducing energy use inefficiencies and improving operational efficiency, can significantly enhance carbon productivity (Yu et al., 2025). This relationship is also consistent with the findings of Lin and Zhou (2022), Gang et al. (2023), and Khan et al. (2023). Moreover, energy efficiency has a greater positive impact on the environment than other initiatives focusing on transitioning to a more sustainable energy system. Relying solely on renewable energy sources is insufficient for achieving a low-carbon economy. Thus, it is imperative to promote changes in consumer behavior regarding energy usage to prevent waste and facilitate its storage for future utilization. In this regard, energy efficiency plays a role in complementing the transition to a low-carbon economy. Additionally, Indonesia's transition to renewable energy has been slow due to inadequate infrastructure and high costs. In contrast, energy efficiency can be implemented as a standalone measure, offering a more cost-effective solution.

The results also show that renewable energy consumption has a significantly positive short- and long-term impact, suggesting that increasing renewable energy can simultaneously reduce emissions and boost the Indonesian economy. Meng et al. (2022)

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found that the development and use of renewable energy on the supply side will gradually promote green consumption, replacing fossil fuel consumption and establishing a new sustainable energy consumption pattern. In addition, adopting renewable energy will reduce pollution and the degradation of natural resources, and support the implementation of new economic concepts such as the circular, low-carbon, or green economy (Wang et al., 2024). This finding aligns with other studies on the relationship between renewable energy consumption and economic development, such as Sohag et al. (2021), Su et al. (2022), and Qamruzzaman & Karim (2024). Next, the impact of renewable energy on carbon productivity was found to be more significant in the long term, as the transition is gradual. The significant long-term impact also results from the accumulation of structural changes over time. Recent research supports this by showing that renewable energy utilization, energy efficiency, and renewable energy technology innovation can systematically improve carbon productivity over time (Tong et al., 2025). Additionally, Indonesia's abundant natural resources, including underutilized renewable energy sources, offer a significant opportunity to increase renewable energy production, potentially amplifying its impact. The long-term deployment of renewable energy also provides a foundation for advancing green technology in economic activities, with substantial impacts on economic growth and emissions reduction.

The use of natural resource rents has also been shown to benefit carbon productivity, both in the short and long term. Chen et al. (2023) observed that such utilization facilitates economic diversification from carbon-intensive to environmentally friendly markets. Moreover, the variable's positive impact may in part be attributed to responsible resource utilization and strict extraction policies. Meanwhile, revenue from natural resources can be reinvested in the clean energy transition and other low-carbon industries, thereby stimulating economic growth while reducing emissions (Khaddage-Soboh et al., 2023). Past studies have also indicated that the environmental implications of resource rents are conditional and may become more favorable when accompanied by effective financial and institutional mechanisms (Chen & Chen, 2024). As a nation bestowed with natural resources, Indonesia has the opportunity to leverage these resource rents to advance sustainable economic development. Such efforts may entail promoting renewable energy, augmenting green investment, encouraging environmentally conscious infrastructure and technology, and providing financing for conservation initiatives. This form of influence is consistent with the findings of Nwani & Adams (2021) and Alfalih & Hadj (2022).

In contrast to the other four variables, globalization has no statistically significant impact on carbon productivity in Indonesia, either in the short or long term. This result may be due to the effects of globalization offsetting each other. On the one hand, globalization can increase carbon productivity by facilitating technology transfer, expanding access to international markets, and promoting efficient production. On the other hand, it can also increase transportation intensity, energy consumption, and carbon-intensive production and consumption. In the Indonesian context, these effects may cancel each other out, resulting in no clear net impact on carbon productivity. Short-term negative trends may reflect pressures from trade expansion and energy-intensive

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adjustments. In contrast, long-term positive trends may indicate that the benefits of international integration take longer to materialize. However, since neither of these impacts is statistically significant, globalization cannot be considered a decisive determinant of carbon productivity in Indonesia.

The ECT coefficient is negative and statistically significant, thereby confirming the validity of the ECM. This result indicates that when carbon productivity deviates from its long-run equilibrium path, the system gradually adjusts towards equilibrium. The estimated speed of adjustment indicates that approximately 74.9 percent of short-run disequilibrium is corrected within 1.34 years, implying a relatively rapid rate of convergence. In practical terms, this result suggests that although temporary shocks may affect carbon productivity in the short run, the underlying long-run relationship remains stable and exerts a strong corrective influence over time. Therefore, the short-run results support the direction of the long-run findings and reinforce the conclusion that carbon productivity in Indonesia follows a stable adjustment path, mainly governed by domestic structural determinants.

CONCLUSION

The results showed that energy transition had the greatest impact on carbon productivity, with energy efficiency and the adoption of renewable energy having positive effects. Financial development was also found to have a positive effect, suggesting that the financial sector can support carbon productivity by promoting efficient capital allocation and investment in cleaner, more productive activities. As an additional variable, natural resource rent had a positive and significant effect, suggesting that resource-based revenues can contribute to carbon productivity when managed effectively and directed towards sustainable development. Meanwhile, globalization did not have a statistically significant impact on carbon productivity in Indonesia. These results indicate that improvements in carbon productivity in Indonesia primarily depend on domestic structural factors rather than external factors.

These findings have clear policy implications. Enhancing energy efficiency should remain a top priority. This can be supported by stricter industrial standards, the adoption of energy-saving technologies, and incentives to improve production and infrastructure efficiency. The expansion of renewable energy also underscores the need for accelerated investment in renewable electricity, grid modernization, and the development of supporting technologies. In the financial sector, policies should promote green financing, expand access to funding for cleaner technologies, and encourage financial institutions to support low-carbon investments. Moreover, natural resource revenues should be managed strategically, directed toward renewable energy, environmental protection, and sustainable infrastructure rather than carbon-intensive activities. Overall, Indonesia's progress in carbon productivity depends primarily on the government's capacity to align energy, financial, and resource governance policies with the country's long-term low-carbon development agenda.

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