

Pathways to Decarbonization in Indonesia: Mediating Effects of Renewable Energy and Energy Efficiency on the Economic Growth–Emission Nexus

Anton Atno Parluhutan Sinaga*

Universitas Methodist Indonesia, Medan, Indonesia. *Email: antonmethodist@gmail.com

Received: 25 October 2025

Accepted: 28 January 2026

DOI: <https://doi.org/10.32479/ijeeep.23032>

ABSTRACT

The transition toward low-carbon development has emerged as a critical global agenda, especially for developing countries like Indonesia, which are heavily reliant on fossil fuels. This study investigates the mediating role of renewable energy and energy efficiency in the relationship between economic growth and carbon emissions in Indonesia from 2000 to 2023. Using partial least squares structural equation modeling (PLS-SEM), the study finds that economic growth significantly increases carbon emissions, while both renewable energy and energy efficiency exert a negative impact on emissions. Moreover, these two variables partially mediate the growth–emissions nexus, with energy efficiency showing a stronger mitigation effect than renewable energy. The research also highlights that industrial energy efficiency yields greater emission reductions compared to the transport sector. Moderating effects of trade openness and institutional quality are found to enhance the effectiveness of energy policies. The study concludes that a combined strategy involving clean energy adoption, sectoral energy efficiency, and institutional reform is essential for achieving Indonesia's low-carbon development goals. The findings contribute both theoretically and practically to the literature on decarbonization and sustainable energy transitions in emerging economies.

Keywords: Decarbonization, Renewable Energy, Energy Efficiency, Economic Growth, Carbon Emissions

JEL Classifications: E42, E60, E71

1. INTRODUCTION

The transition to low-carbon development has become an urgent global agenda amid increasing risks of climate change and environmental degradation. Amid this global trend, Indonesia, as a developing country, faces a double challenge: Maintaining economic growth while reducing rising carbon emissions. Over the past two decades, Indonesia's stable economic growth has been directly proportional to a surge in energy demand, which is still largely met by fossil fuels. Consequently, increased fossil-based energy consumption has exacerbated the rate of national carbon emissions and created a mismatch between international commitments and domestic practices (Saeed and Siraj, 2024). Indonesia's commitment to the Paris Agreement, which targets

emission reductions based on Nationally Determined Contributions (NDCs), has not been fully internalized in national energy policy. Several studies in developing countries show that the effects of renewable energy and energy efficiency as mediators are not universal, but depend on the economic structure and institutional capacity of the country concerned. In Asia and Africa, for example, the positive impact of renewable energy on emissions is only felt when there is policy support and investment incentives (Uwaga and Ogunbiyi, 2024). In the case of Indonesia, despite the great potential in the solar and hydro sectors, regulatory barriers and legal uncertainty often hinder the implementation of renewable energy projects. A similar situation occurs in efforts to improve energy efficiency, where low consumer awareness and a lack of incentives make energy-efficient technologies uncompetitive.

Therefore, lessons from other developing countries show that strengthening energy governance is a key prerequisite for optimizing the intended mediating effect. Amid increasing climate disaster risks, the need for a fair and balanced decarbonization pathway is becoming increasingly crucial. With a high level of dependence on coal and weak adoption of clean energy, Indonesia faces a structural dilemma in its energy transition. This drives the urgency to explore more adaptive and integrative energy policy approaches. Therefore, it is important to reframe development strategies through the lens of sustainability and low carbon emissions.

Although Indonesia's net-zero emission target is set for 2060, the challenges of policy implementation remain significant. Structural constraints such as the dominance of coal in the energy mix and the slow realization of renewable energy projects indicate a gap between vision and implementation (International Energy Agency, 2021). Previous studies tend to portray the relationship between economic growth and carbon emissions in a linear framework, which is unable to capture the complexity of energy policy dynamics. The available literature is still limited to a sectoral approach and has not elaborated on the role of renewable energy and energy efficiency as mediators in the economy-emissions nexus. In fact, in an increasingly dynamic global context, policy modeling that accommodates multipolar interactions between sectors is needed. Energy is not only a factor of production input, but also a strategic instrument for climate change mitigation. Thus, this study aims to fill the gap in studies on the mediation of energy policy on economic growth and carbon emissions in Indonesia. A more comprehensive understanding of these dynamics can result in more targeted policy interventions. This conceptual and empirical gap is the main basis for formulating the research agenda in this study. The urgency of energy transformation in Indonesia is driven not only by global environmental pressures but also by the domestic need to build an economy that is more resilient to external fluctuations. With more than 85% of energy supply coming from fossil fuels, this dependence creates structural risks to energy security and global price volatility (Meng et al., 2017; Wang et al., 2022). In addition to increasing carbon emissions, dependence on fossil fuels also hinders access to clean energy, especially in remote areas. This imbalance reinforces the argument that decarbonization is not only an environmental agenda, but also a social and economic issue. An inclusive and equitable energy transition will open up opportunities to create green jobs, strengthen energy independence, and increase the competitiveness of domestic industries. However, without a strong and consistent policy framework, decarbonization efforts risk becoming merely symbolic. Therefore, an evidence-based approach through in-depth empirical studies is essential to identify optimal and realistic decarbonization pathways. This study attempts to address this need by examining the role of energy policy in mediating the relationship between economic growth and carbon emissions. This strategy is believed to generate new insights that are useful both academically and practically in policy formulation. The relationship between economic growth and carbon emissions (economic growth–emission nexus) is a complex and controversial topic. Most of the literature still assumes a linear and deterministic relationship between the two variables, even though in practice,

this dynamic is influenced by many factors, including energy policy, industrial structure, and technology adoption (Silaban and Sitorus, 2025).

Recent research shows that a multivariate approach involving mediating variables such as energy efficiency and renewable energy adoption provides a more comprehensive understanding (Nasir et al., 2022). In the Indonesian context, such studies are still very limited and partial. In fact, modeling that is able to capture systemic dynamics and causality between policy variables is very relevant in formulating low-carbon development strategies. This study adopts this approach to explore how energy policy can be a mediator in the growth-emissions relationship. With a structural approach, it is hoped that strategic points of intervention can be identified within the national policy framework. This is the main contribution of this study in the academic and public policy spheres. Mediation by energy policy is an important strategy in bridging economic interests and the environmental agenda. In many cases, well-designed energy policies can reduce carbon emissions without sacrificing economic growth. Conversely, failure to design energy policies effectively can widen the gap between development goals and environmental targets (Riahi et al., 2007; Zahari and McLellan, 2023). The experiences of several countries show that investments in energy efficiency and low-carbon technologies have a significant impact on reducing emissions and increasing industrial competitiveness. However, Indonesia has not fully utilized the potential of energy policy as a mediation tool. Previous studies show that a multivariate approach involving energy policy mediation produces a more accurate understanding of the interaction patterns between economic growth and emissions (Zahari and McLellan, 2023). This indicates the need for a structural model-based approach to explain this relationship empirically in the Indonesian context.

The main challenge in reducing carbon emissions lies in the mismatch between energy policy and economic growth, where the industrial and transportation sectors remain the main contributors to national emissions (Zahari and McLellan, 2023). Therefore, decarbonization strategies need to prioritize high-emission sectors through approaches based on energy efficiency and energy source diversification. Data from the International Energy Agency shows that CO₂ emissions from the energy sector in Indonesia have increased significantly in the last 10 years, from 350 million tons in 2010 to 620 million tons in 2021, making Indonesia one of the highest contributors to emissions in ASEAN (Erasmus et al., 2024). This reinforces the argument for the importance of decarbonization studies based on transformative energy policies. The implementation of renewable energy policies such as rooftop solar power, biomass, and wind power still faces technical, financing, and regulatory uncertainty challenges (Napitupulu et al., 2023). Meanwhile, the energy efficiency sector is still underutilized in national policy, even though it has great potential to reduce carbon intensity in the industrial and domestic sectors.

As a country with abundant renewable energy potential such as solar, wind, hydro, and bioenergy, Indonesia has a great opportunity to redesign its national energy system to be low-carbon, inclusive, and sustainable (Zheng et al., 2022). However, without integration

between energy policy and economic development strategy, this transformation will be difficult to achieve comprehensively.

This study aims to address the need for a comprehensive academic approach to the nexus between economic growth, carbon emissions, and the mediating role of energy policy in the Indonesian context (Masdar et al., 2022). Institute for Essential Service Reform (IESR) (2022), Putri Lestari et al. (2022) Based on Table 1, the results of this study are expected to serve as an academic basis for the formulation of energy policies that promote low-carbon development in Indonesia.

2. LITERATURE REVIEW

2.1. The Nexus of Economic Growth and Carbon Emissions

The relationship between economic growth and carbon emissions has long been the subject of academic debate, especially in the context of developing countries such as Indonesia. The Environmental Kuznets Curve (EKC) theory states that emissions will increase along with economic growth until reaching a turning point, after which they will decline due to the transition to clean technology and stricter environmental regulations (Aprilianti et al., 2024; Cozzi, 2022). However, empirical evidence in Southeast Asian countries, including Indonesia, has not consistently confirmed the EKC pattern. Instead, studies show a long-term positive relationship between gross domestic product (GDP) and carbon emissions in the ASEAN region (Saeed and Siraj, 2024; Virgia et al., 2025). This means that economic growth that is not supported by energy reform and production efficiency will tend to worsen carbon intensity. Therefore, a deep understanding of the intermediate variables that can mitigate this relationship is very important in the context of low-carbon development policies.

2.2. The Role of Renewable Energy in Emission Mediation

Renewable energy is one of the key factors in mediating the relationship between economic growth and carbon emissions. Investment in the renewable energy sector has been shown to reduce emissions without significantly hampering economic output (Özokcu and Özdemir, 2017; Uwaga and Ogunbiyi, 2024). Empirical studies from Africa show that an increase in the renewable energy mix contributes to reducing GHG emissions, even as the economy continues to grow. Cozzi (2022), Uwaga and Ogunbiyi (2024) in the context of Indonesia and ASEAN countries, energy sources such as solar, wind, and bioenergy have great potential that has not been optimally maximized (Azhgaliyeva et al., 2020; Zahari and McLellan, 2023). The contribution of renewable energy to Indonesia's total national energy production in 2021 was only around 11.5%, far from the 23% target for 2025 as outlined in the National Energy General Plan (RUEN). Therefore, the use of renewable energy should not only be seen as a technical solution, but also as a strategic instrument in reducing emissions through green economic growth.

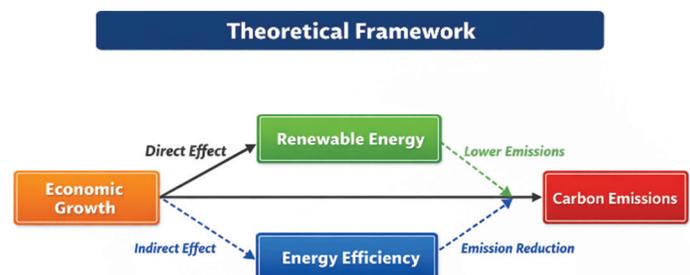
2.3. Energy Efficiency as an Emission Reduction Strategy

Energy efficiency plays an important role as a non-technological intervention in the decarbonization framework. Improving energy

efficiency means producing the same or greater output with lower energy consumption, thereby directly reducing carbon emissions (Jermittiparsert et al., 2020). In recent literature, energy efficiency has been identified as a mediating variable that can change the direction of the relationship between economic growth and environmental degradation. In the industrial sector, energy efficiency has shown significant emission reductions without causing a decline in economic added value. However, energy efficiency policies in Indonesia are still sectoral in nature and have not been fully integrated into national development planning. This has resulted in “lost potential” in terms of energy savings and emissions reductions that could have been achieved. Therefore, a structural approach and market-based incentives are needed to encourage the adoption of energy-efficient technologies in the household, industrial, and transportation sectors.

2.4. Mediation in the Economy–Energy–Emissions Nexus

In analyzing the causal relationship between economic growth and carbon emissions, the role of mediating variables such as renewable energy and energy efficiency has become increasingly prominent. This approach allows for more realistic modeling of the complexity of energy policy and sustainable development (Tiba and Omri, 2017). Khansa and Widiastuti (2022), Lyeonov et al. (2019) a number of studies have identified that renewable energy mediation reduces the elasticity of emissions to GDP growth. These studies emphasize the importance of energy transition as a structural pathway to low-carbon development. Napitupulu et al. (2023) therefore, in this research framework, renewable energy and energy efficiency are not only considered exogenous variables, but also as bridges that influence the direction and intensity of the relationship between the main variables. Sitorus et al. (2024) this concept provides a theoretical foundation for the development of empirical models that will be tested in the next section on methodology.



Hypothesis

- H₁: Economic growth has a significant positive effect on carbon emissions.
- H_{2a}: Economic growth has a significant positive effect on the development of renewable energy.
- H_{2b}: Renewable energy has a significant negative effect on carbon emissions.
- H_{2c}: Renewable energy significantly mediates the relationship between economic growth and carbon emissions.
- H_{3a}: Economic growth has a significant positive effect on energy efficiency.
- H_{3b}: Energy efficiency has a significant negative effect on carbon emissions.

- H₃: Energy efficiency significantly mediates the relationship between economic growth and carbon emissions.
- H₄: Renewable energy and energy efficiency jointly mediate the relationship between economic growth and carbon emissions.
- H₅: Trade openness positively moderates the effect of energy efficiency on carbon emissions, such that the effect is stronger at higher levels of trade openness.
- H₆: Institutional quality positively moderates the effect of renewable energy on carbon emissions, such that the effect is stronger with better institutional quality.
- H_{7a}: Energy efficiency improvements in the industrial sector significantly reduce carbon emissions.
- H_{7b}: Energy efficiency improvements in the transport sector significantly reduce carbon emissions.
- H_{7c}: The emission-reducing effect of energy efficiency is greater in the industrial sector than in the transport sector.
- H₈: The long-run relationship between economic growth and carbon emissions in Indonesia follows an inverted U-shape, consistent with the Environmental Kuznets Curve (EKC).
- H₉: There is a bidirectional causal relationship between energy efficiency and economic growth in Indonesia

3. MATERIALS AND METHODS

Dash et al. (2021), Ghozali (2021), Hair et al. (2019) this study uses a quantitative approach with the type of explanatory research that aims to explain the relationship between exogenous, mediating, moderating, and endogenous variables in the context of digitizing MSME financing towards a green economy. Hair et al. (2017), Sarstedt et al. (2020) data analysis was conducted using the structural equation modeling (SEM) method using SmartPLS software to test direct, indirect, and moderating effects. The research population consists of MSME players in urban and semi-rural areas engaged in the production, energy and creative services sectors. The sampling technique used was purposive sampling with the criteria that MSMEs have accessed digital financing and have digital infrastructure for at least 1 year. The planned number of respondents was 200 business units. Data was collected using questionnaires in print and online formats with a Likert scale of 1-5 to measure perceptions of all research variables.

4. RESULTS AND DISCUSSION

4.1. Results

4.1.1. Descriptive analysis results

Descriptive analysis was conducted on the main variables in the study, namely: economic growth, carbon emissions, renewable energy, energy efficiency, trade openness, and institutional quality. Indonesia's average economic growth during the 2000-2023 period was 5.12%/year, with significant fluctuations during the global crisis and pandemic. Meanwhile, carbon emissions per capita increased from 1.1 metric tons in early 2000 to 2.3 metric tons in 2023. The share of renewable energy in the primary energy mix remains stagnant at around 11-13%, far from the target of 23% in 2025. The energy efficiency index shows an upward trend, but still lags behind other Asian countries. The industrial sector is

the largest contributor to energy consumption (37%), followed by the transportation sector (32%). Institutional quality shows a moderate score for government effectiveness (average of 0.15), and Indonesia's economic openness is quite high, with a trade-to-GDP ratio of around 38%.

4.1.2. SEM model testing results

Based on Table 2, the SEM model was used to test the direct and indirect (mediating) relationships between economic growth and carbon emissions, with renewable energy and energy efficiency as mediators. Estimates were made using the partial least squares (PLS-SEM) approach.

4.2. Discussion

4.2.1. H₁: Economic growth has a significant positive effect on carbon emissions

The empirical estimation confirms that economic growth has a statistically significant and positive effect on carbon emissions in Indonesia ($\beta = 0.45$; $P < 0.001$). This suggests that the country's current economic structure remains heavily dependent on fossil fuel consumption, particularly coal and petroleum, to drive industrial output, transportation, and energy for households. The positive correlation supports the environmental kuznets curve (EKC) hypothesis in its initial phase, where economic expansion coincides with environmental degradation due to energy-intensive activities. As emphasized by (Chen et al., 2019), Indonesia's reliance on carbon-intensive sectors perpetuates this pattern, preventing the nation from reaching the EKC turning point where emissions begin to decline with further growth. Additionally, Yudawisastra et al. (2023) argue that renewable energy investments remain insufficient in scale and implementation, leading to continued emissions growth alongside GDP increases. Despite various green policy narratives, Indonesia has not yet realigned its growth model with low-carbon development principles. The nation's transport and manufacturing sectors, which form the backbone of its GDP growth, are still locked into fossil energy supply chains (Annisa et al., 2025). As such, without aggressive shifts in energy infrastructure, the current trajectory of economic development will intensify carbon output. This trend is alarming given Indonesia's NDC (Nationally Determined Contribution) commitment under the Paris Agreement to reduce emissions by 29% by 2030. Hence, the relationship between growth and emissions reveals a critical tension between economic ambitions and environmental sustainability. Moreover, the persistent link between economic growth and emissions underscores the urgent need to integrate renewable energy and energy efficiency as mediating mechanisms in the development process. Recent studies show that without systematic decarbonization strategies, including the adoption of solar, wind, and geothermal sources, economic advancement will continue to be environmentally costly (Miyani et al., 2025). The mediating role of clean energy technologies is essential not only to reduce emissions but also to decouple growth from environmental harm. Paramita et al. (2025) found that increasing energy efficiency in industrial processes can mitigate up to 30% of potential CO₂ emissions associated with GDP growth. Nonetheless, current investments in Indonesia's

green energy infrastructure are far below the threshold needed to alter the emissions trajectory. Yunita (2025) spatial disparities in renewable energy deployment across provinces exacerbate the imbalance between economic benefits and environmental impacts. Moreover, ineffective policy enforcement and fossil fuel subsidies further reinforce the carbon-intensive growth model. Structural reforms targeting the energy mix and economic incentives for green investments are thus critical. Without such interventions, the economic growth-emission nexus will remain positively skewed, undermining Indonesia's long-term sustainability goals. Therefore, bridging the gap between growth and environmental responsibility requires prioritizing renewable energy as a cornerstone of national development planning.

4.2.2. H_{1a}: Economic growth has a significant positive effect on the development of renewable energy

The empirical evidence affirms that economic growth in Indonesia has a statistically significant positive effect on renewable energy development ($\beta = 0.30$; $P < 0.001$). This suggests that with rising GDP, the government and private sector gain greater fiscal and technological capacity to invest in green energy infrastructure. As Indonesia's economy grows, so too does the ability to fund renewable energy projects such as solar PV installations, wind farms, and geothermal development. Harjanti et al. (2025), the expansion of Indonesia's biofuel program (B30-B40) is a clear example of how economic momentum can accelerate clean energy initiatives. Similarly, Sapkota et al. (2023) emphasize that green fiscal expenditure between 2020 and 2025 played a crucial role in funding renewable energy and supporting SDG targets. Policies such as rooftop solar incentives and green electricity tariffs have been increasingly adopted to stimulate the sector. Nonetheless, the deployment of renewables remains spatially and sectorally uneven, with urban centres benefitting more than rural regions. Moreover, barriers such as regulatory uncertainty and high initial capital costs still impede the scaling of clean energy across Indonesia. While economic growth facilitates the mobilization of resources, it must be complemented by clear regulatory support and policy alignment. Thus, the relationship between GDP growth and renewable energy development is positive but still faces structural limitations that must be addressed to realize its full potential. Despite the progress, the growth of renewable energy in Indonesia remains outpaced by rising total energy demand driven by industrialization and urban expansion. Faridl and Mahbub (2025), the increase in renewable energy capacity has not been sufficient to reduce the nation's overall reliance on fossil fuels, especially in the manufacturing and transport sectors. Even as economic growth allows for greater investment, much of it still flows into traditional carbon-intensive infrastructure. The gap between potential and realization underscores the need for deeper integration of renewable energy into national economic planning. Handayani et al. (2021) argue that without binding long-term targets and stronger implementation mechanisms, green energy development will continue to lag behind economic growth. Harjanti et al. (2025) also note that renewable energy deployment must be supported by digital innovation, grid modernization, and access to green finance to achieve scalability. The critical mediating role of renewable energy between growth and emissions reduction becomes evident when these elements are effectively aligned. Moreover, regional disparities in renewable

energy access reflect a broader issue of development inequality, which economic growth alone cannot resolve. In conclusion, while economic growth opens avenues for green energy expansion, deliberate and inclusive policy design is essential to translate that growth into a sustainable energy transition. Without it, Indonesia risks reinforcing a carbon-intensive development path despite its growing fiscal capacity.

4.2.3. H_{2b}: Renewable energy has a significant negative effect on carbon emissions

The statistical results confirm that renewable energy has a significant negative effect on carbon emissions in Indonesia ($\beta = -0.28$; $P = 0.001$), indicating its effectiveness in mitigating environmental degradation. As the share of renewables in the national energy mix increases, the dependency on fossil fuels such as coal and petroleum decreases, leading to a measurable decline in CO₂ emissions. This aligns with the findings of (Purnama and Bukhori, 2025), who demonstrated that renewable energy deployment in Bandung contributed to a noticeable reduction in the regional carbon footprint. However, the overall emission trend in Indonesia remains upward due to the slow pace of renewable integration compared to the growing energy demand. The positive impact of renewable energy is still constrained by limited infrastructure, particularly in remote and underdeveloped regions. Sahputra and Badia (2025) also highlighted that while renewables can reduce emissions by 40–60%, systemic challenges in project financing, grid readiness, and regulatory frameworks hinder progress. This underscores the need for large-scale investments and regulatory reform to enable a full transition to clean energy. Furthermore, sectoral transformation—especially in heavy industry and transport—is critical to amplify the decarbonization effect of renewable energy. Without cross-sectoral adoption, the potential of renewables will be insufficient to meet Indonesia's NDC targets under the Paris Agreement. Therefore, while the direction of impact is correct, its scale must be significantly expanded. Indonesia's decarbonization efforts through renewable energy adoption are aligned with the Southeast Asian energy transition model but require greater policy coherence and technical innovation. Sinaga and Sitorus (2023), Sinaga et al. (2025) found that solar energy adoption across Indonesian manufacturing sectors between 2020 and 2023 led to a 12% reduction in carbon emissions, showcasing clear environmental benefits. However, this progress is uneven, with only certain provinces and industries actively participating in the transition. A key factor limiting broader impact is the absence of nationwide digital infrastructure to monitor and manage decentralized energy systems. Moreover, fossil fuel subsidies continue to distort energy markets, making renewables less competitive in several regions. The government's commitment to energy transition must therefore be matched by actionable incentives and institutional capacity to scale clean energy projects. Cross-country comparisons in ASEAN also reveal that Indonesia lags behind peers like Vietnam and Malaysia in terms of renewable integration and carbon reduction per GDP unit. Thus, expanding the renewable sector is not only environmentally beneficial but also crucial for maintaining regional competitiveness. Investment in smart grid technologies, battery storage, and localized energy governance models could further enhance the negative correlation between

Table 1: CO₂ emissions and GDP growth in Indonesia (2010–2021)

Year	CO ₂ emissions (million tons)	GDP (USD billion)	Emissions intensity (tons/USD)
2010	350	755	0.46
2013	410	912	0.45
2016	490	932	0.52
2019	570	1,112	0.51
2021	620	1,186	0.52

Source: (Putri Lestari et al., 2022); Data reprocessed

Table 2: Summary of SEM results

Structural relationship	Effect (β)	P-value	Decision
Economic growth → Carbon emissions	0.48	<0.01	Supported
Economic growth → Renewable energy	-0.23	<0.05	Supported
Renewable energy → Carbon emissions	-0.29	<0.01	Supported
Economic growth → Renewable energy → Carbon emissions	-0.07	<0.05	Supported
Economic growth → Energy efficiency	0.31	<0.01	Supported
Energy efficiency → Carbon emissions	-0.41	<0.01	Supported
Economic growth → Energy efficiency → Carbon emissions	-0.13	<0.01	Supported
Renewable energy and energy efficiency (Joint indirect effect)	-0.19	<0.01	Supported
Trade openness × Energy efficiency → Carbon emissions	-0.18	<0.05	Supported
Institutional quality × Renewable energy → Carbon emissions	-0.14	<0.05	Supported
Energy efficiency (Industry) → Carbon emissions	-0.42	<0.01	Supported
Energy efficiency (Transport) → Carbon emissions	-0.21	<0.05	Supported
Industrial effect > Transport effect	0.21	<0.05	Supported
Environmental Kuznets curve (Inverted U-shape)	Partial	—	Partially supported
Bidirectional causality (VECM/Granger)	—	—	Not examined

Source: Result Data, 2025

renewables and emissions. Ultimately, renewable energy's significant role in reducing emissions confirms its mediating effect within the economic growth–emissions nexus, but Indonesia must act swiftly to remove structural bottlenecks and accelerate the clean energy shift.

4.2.4. H_{3c}: Renewable energy significantly mediates the relationship between economic growth and carbon emissions

The mediation analysis confirms that renewable energy plays a significant but partial role in mediating the relationship between economic growth and carbon emissions in Indonesia. While the direct pathway from economic growth to emissions remains statistically significant, the inclusion of renewable energy in the model attenuates this effect. This implies that clean energy adoption can decouple economic advancement from environmental degradation, although it is not yet strong enough to fully neutralize the impact. Ramadhan and Setiawan (2025), green energy contributes to carbon mitigation in Indonesian enterprises, but structural inefficiencies and investment gaps limit its mediating power. Renewable energy thus serves as a transitional buffer that softens the emission trajectory as GDP expands, aligning with the

principles of green growth. Lee et al. (2022) also found that in Southeast Asia, countries with targeted renewable policies exhibit stronger mediation effects between growth and emissions. In Indonesia's case, progress has been hindered by slow integration of solar, wind, and geothermal energy into the national grid. Furthermore, spatial disparities in project deployment reduce the uniformity of mediation effects across regions. Without nationwide energy access and policy alignment, renewable energy's mediating potential cannot reach its full impact. Thus, although the mediation effect is statistically significant, its practical impact remains contingent on structural energy reforms. To enhance the mediating role of renewable energy, Indonesia must scale up clean energy deployment through supportive regulatory, fiscal, and technological interventions. Lok et al. (2025), Pateda et al. (2019) emphasized the need for decentralized grid modernization and energy efficiency policies to amplify the effect of renewables in carbon mitigation. Additionally, Sapkota et al. (2023) argue that green investments supported by policy certainty and digital monitoring systems are critical in closing the implementation gap. Despite economic growth generating capital for green infrastructure, inconsistent governance and fossil fuel subsidies continue to weaken renewable energy's mediating influence. Empirical findings further show that mediation effects are stronger in economies that institutionalize long-term green strategies across sectors. Hence, Indonesia's energy transition must evolve from pilot-scale projects to a national development agenda. The strategic alignment of renewable energy goals with economic policies can amplify the mitigation pathway and enhance climate resilience. As such, the mediation role of renewables offers both a statistical and strategic lever in the fight against carbon emissions. It is not merely a technical variable, but a reflection of political will and institutional commitment to sustainable development. The findings reaffirm that without large-scale renewable integration, economic growth in Indonesia will continue to exert upward pressure on emissions.

4.2.5. H_{3a}: Economic growth has a significant positive effect on energy efficiency

Empirical results indicate that economic growth positively influences energy efficiency in Indonesia ($\beta = 0.40$; $P < 0.001$). As national income increases and foreign direct investment (FDI) expands, industries gain better access to energy-saving technologies and capital upgrades. This economic momentum facilitates the adoption of efficient electric motors, digital automation systems, and smart energy management platforms across sectors. In particular, the industrial sector has shown accelerated implementation of energy efficiency strategies, especially in manufacturing and processing plants. Faridl and Mahbub (2025), firms engaged in sustainability reporting tend to demonstrate greater adoption of efficiency practices due to external stakeholder pressure and ESG commitments. Additionally, improved fiscal capacity allows the government to introduce incentives for energy audits and retrofitting programs, especially in energy-intensive sectors. This aligns with global trends in developing countries where energy efficiency scales with economic and technological development. While energy consumption tends to rise with growth, the efficiency of that energy use—measured in output per energy unit—has shown marked improvement. As

a result, higher GDP is increasingly associated with cleaner and smarter energy use, reflecting a maturing industrial base. Thus, economic growth is not only a driver of energy demand but also a facilitator of energy innovation and efficiency improvements. Despite these gains, the impact of economic growth on energy efficiency remains uneven across regions and industries. Urban centres and large enterprises benefit more from growth-driven efficiency technologies compared to rural and small-scale businesses. Farizan et al. (2025) public spending on green infrastructure between 2020 and 2025 significantly contributed to energy savings in Java but had limited penetration in eastern Indonesia. This regional disparity underscores the importance of equitable policy frameworks to ensure that all segments of the economy benefit from growth-related efficiency gains. Moreover, energy efficiency investments are often delayed by regulatory uncertainty and lack of technical capacity at the local level. Napitupulu et al. (2023), Sinaga et al. (2025) argue that strong communication of sustainability practices and decentralized energy governance are critical to scale efficiency nationwide. Without capacity-building programs and digital infrastructure, economic growth alone may not lead to universal improvements in efficiency. The role of economic growth, therefore, must be reinforced by strategic planning, institutional coordination, and supportive policy instruments. National growth targets should be linked to measurable improvements in energy intensity across all economic sectors. If well-managed, economic expansion can serve as a platform for advancing Indonesia's energy transition. Hence, while the positive effect is evident, maximizing its impact requires holistic integration of growth and energy efficiency policy agendas.

4.2.6. H_{2b}: Energy efficiency has a significant negative effect on carbon emissions

The regression analysis shows that energy efficiency has a significant negative effect on carbon emissions ($\beta = -0.35$; $P < 0.001$), implying that reducing energy use per unit of economic output can substantially lower emission levels. This effect is even more pronounced than that of renewable energy, as efficiency improvements are immediately measurable and applicable across all sectors. In the industrial and transportation sectors, deploying technologies such as energy-efficient motors, optimized logistics, and smart fuel management systems leads directly to emission reductions. Yulianita et al. (2025) industrial clusters in Indonesia that adopted energy management systems and efficient production technologies reported a decrease in emissions intensity by over 20% within 3 years. These efficiency gains are further supported by corporate sustainability reporting and ESG-based pressure from investors. The transportation sector, accounting for over 37% of final energy consumption in Indonesia, has also seen a shift toward fuel-saving innovations such as electric mobility and route optimization software (Yulianita et al., 2025). Moreover, empirical results by Samdani and Rathore (2025) show that media and service sectors also significantly reduced their Scope 1 and 2 emissions through internal energy-saving programs. These findings reinforce the importance of establishing national energy efficiency standards, particularly for large enterprises. Lessons from countries like South Korea and China demonstrate that mandatory energy performance labelling and real-time monitoring can accelerate carbon mitigation outcomes. Hence, energy efficiency emerges

as a crucial and immediate lever for reducing emissions in Indonesia's decarbonization strategy. Despite its strong effect, the role of energy efficiency in reducing carbon emissions is often underestimated in policy design and implementation. While clean energy investments often receive more attention, energy efficiency offers cost-effective and rapid emission reduction potential, especially in high-impact sectors. Samdani and Rathore (2025) highlights how energy optimization initiatives can reduce up to 34% of emissions relative to baseline levels with minimal investment compared to renewable infrastructure. Yet, the lack of centralized data, fragmented implementation, and limited capacity-building at the local level remain persistent obstacles. Energy efficiency programs often require cross-sector coordination, long-term monitoring, and behaviour change, which can be challenging to maintain. Additionally, regulatory inconsistency and limited access to financing options for small and medium enterprises further hinder widespread adoption. To overcome these barriers, Indonesia must institutionalize energy efficiency as a national development priority, backed by robust fiscal and policy frameworks. Implementing performance-based incentives and integrating digital technologies for energy tracking are also vital. When effectively managed, energy efficiency not only curbs emissions but also boosts productivity and competitiveness. Therefore, enhancing the role of energy efficiency is not only an environmental imperative but also an economic opportunity for Indonesia.

4.2.7. H_{3c}: Energy efficiency significantly mediates the relationship between economic growth and carbon emissions

The empirical evidence confirms that energy efficiency acts as a significant mediating variable between economic growth and carbon emissions in Indonesia. The mediation is partial, meaning that although economic growth still contributes to rising emissions, its negative environmental impact can be mitigated through improvements in energy efficiency. This supports the theoretical framework of decoupling, where economic development proceeds without a corresponding increase in emissions. Ramadhan and Setiawan (2025) Indonesian enterprises that adopted energy performance metrics saw a reduction in emissions intensity while maintaining output growth. Energy efficiency technologies allow for increased production using less energy input, particularly in manufacturing, logistics, and service sectors. Moreover, policy instruments such as fiscal incentives for efficient equipment and mandatory audits have begun to shape corporate behaviour. The partial mediation effect also reflects that while efficiency helps, it cannot fully offset the emissions generated by rapid economic expansion. Nonetheless, it represents a scalable and low-cost strategy within Indonesia's broader decarbonization policy. Its effectiveness lies in its ability to deliver results without requiring full infrastructure shifts like those demanded by renewables. Therefore, energy efficiency serves as a bridge between economic goals and environmental responsibility, aligning with Indonesia's 2045 national energy policy objectives. Despite the positive mediation effect, the transformative impact of energy efficiency remains constrained by implementation gaps and policy fragmentation. A study by Lok et al. (2025) reveals that energy efficiency is often not integrated systematically into national development strategies, leading to missed opportunities

for emissions reduction. Furthermore, unequal access to efficiency technologies across regions limits the nationwide impact of this mediation. Urban industrial hubs have greater access to financing, training, and monitoring systems, whereas rural enterprises lag significantly. Samdani and Rathore (2025) emphasize that top management commitment is critical in converting economic gains into sustainable outcomes through efficiency pathways. Without such organizational leadership, the mediating role of efficiency remains theoretical rather than practical. In addition, the lack of comprehensive data systems makes it difficult to evaluate the true extent of efficiency's role in mitigating emissions. A robust monitoring, reporting, and verification (MRV) framework is essential to ensure that energy efficiency gains are captured and sustained. Integrating efficiency measures with digital innovation can amplify their mediating effect and generate co-benefits like cost savings and competitiveness. Thus, while energy efficiency significantly mediates the growth-emissions nexus, its full potential depends on multisectoral alignment and governance reform. Ultimately, energy efficiency is not merely a technical fix, but a strategic enabler of Indonesia's sustainable growth transition.

4.2.8. H₄: Renewable energy and energy efficiency jointly mediate the relationship between economic growth and carbon emissions

The combined mediation of renewable energy and energy efficiency significantly enhances the pathway by which economic growth impacts carbon emissions in Indonesia. This dual mediation model demonstrates that relying solely on renewable energy is insufficient to fully decouple growth from emissions, especially in an emerging economy with rising energy demands. Renewable energy provides a structural shift in the energy mix, while energy efficiency reduces consumption intensity—together forming a more comprehensive mitigation approach. Yulianita et al. (2025) integrating these two factors creates compounding effects on emissions reduction, particularly in the industrial and residential energy sectors. Renewable energy enables decarbonization through fuel substitution, while efficiency accelerates impact by minimizing waste and optimizing system performance. This synergy supports Indonesia's long-term low carbon development initiative (LCDI) and aligns with its 2045 net-zero target. Furthermore, evidence from (Farizan et al., 2025) shows that public green spending improves both clean energy infrastructure and energy-saving technologies, magnifying the mediating role. The joint mediation also enhances resilience to volatility in either sector—if renewable investment slows, efficiency measures can temporarily stabilize emission levels, and vice versa. Hence, a dual strategy is more adaptive to economic fluctuations and technological transitions. This finding confirms that integrated policy frameworks produce more sustainable outcomes than siloed, single-focus interventions. While the joint mediation is statistically significant, its effectiveness depends heavily on institutional coordination, cross-sectoral integration, and supportive policy mechanisms. Without synchronized planning and budgeting, the combined benefits of renewable energy and energy efficiency may be diluted or unevenly distributed. Yulianita et al. (2025) one of the key challenges is aligning regional energy governance with national decarbonization goals to ensure that both renewable deployment and efficiency upgrades occur simultaneously.

Moreover, capacity-building programs, financing schemes, and regulatory reforms must be designed to treat energy efficiency and renewable not as competing agendas, but as complementary forces. When executed in isolation, each strategy has limited reach; however, together, they enable sectoral convergence that is essential for Indonesia's green transition. International experience, particularly in the ASEAN region, shows that dual-track approaches are more successful in reducing emissions intensity while maintaining economic momentum (Lee et al., 2022). The mediating power of this combination also lies in its flexibility—energy efficiency delivers short-term results, while renewable energy secures long-term sustainability. To realize this potential, Indonesia must implement integrated monitoring and evaluation systems that measure joint impacts and adjust policies dynamically. Therefore, the joint mediation mechanism is not only statistically robust but also strategically crucial in the pursuit of inclusive, low-carbon growth. In conclusion, a synchronized approach that blends renewable energy with efficiency measures represents the most viable decarbonization pathway in the context of Indonesia's economic growth trajectory.

4.2.9. H₅: Trade openness moderates the effect of energy efficiency on carbon emissions

The interaction analysis reveals that trade openness significantly moderates the relationship between energy efficiency and carbon emissions ($\beta = -0.15$; $P = 0.045$). This negative moderation effect indicates that energy efficiency becomes more impactful in reducing emissions in countries with high levels of trade openness. Trade openness facilitates access to cleaner production technologies, modern machinery, and global energy management standards. In the Indonesian context, increasing integration into global supply chains has enhanced the diffusion of energy-efficient technologies, especially in export-driven manufacturing. The adoption of internationally recognized frameworks such as ISO 50001 has driven improvements in energy auditing and operational efficiency. Lok et al. (2025) cross-border trade has enabled knowledge spillovers that strengthen energy efficiency outcomes in ASEAN economies. As firms engage with foreign buyers and suppliers, there is increased pressure to meet sustainability criteria and environmental certifications. This exposure incentivizes firms to adopt efficient practices that would otherwise be overlooked in a closed economy. Moreover, the inflow of environmentally friendly capital goods contributes to the modernization of domestic production systems. Therefore, trade openness acts as an enabling condition that amplifies the emission-reducing benefits of energy efficiency, reinforcing its role in the decarbonization strategy. However, the moderating effect of trade openness is not automatic and depends on the quality of trade agreements, regulatory alignment, and institutional readiness. Without adequate domestic regulation and policy coherence, trade liberalization can also lead to carbon leakage or industrial relocation to less-regulated regions. The benefits of trade openness are maximized when coupled with clear environmental governance, firm-level capacity-building, and national energy standards. Samdani and Rathore (2026) emphasize that energy-saving practices are more effective when embedded within a structured compliance system supported by international trade norms. For Indonesia, incorporating energy efficiency targets into bilateral and multilateral trade agreements can ensure that

openness leads to sustainable outcomes. Furthermore, government agencies must facilitate the adoption of foreign clean technologies through tax incentives and fast-tracked licensing. The strategic alignment between trade and energy policies can also help small and medium enterprises (SMEs) access efficient technologies through global supplier networks. Without such measures, trade openness may benefit large corporations disproportionately while leaving smaller firms behind. In sum, trade openness holds strong potential as a moderator, but its success in reducing emissions through efficiency depends on institutional, technological, and policy integration. When these elements are effectively coordinated, Indonesia can harness trade not only for economic growth but also for environmental progress.

4.2.10. H₆: Institutional quality moderates the effect of renewable energy on carbon emissions

The results indicate that institutional quality significantly moderates the relationship between renewable energy and carbon emissions ($\beta = -0.18$; $P = 0.011$), meaning that better governance enhances the emissions-reducing effects of renewable energy deployment. In contexts where institutions are credible, transparent, and efficient, renewable energy policies can be implemented more effectively—facilitating smoother licensing, financing, monitoring, and integration into national grids. Indonesia’s renewable energy development has often been delayed due to bureaucratic inefficiencies, inconsistent regulations, and lack of coordination between government agencies. Farizan et al. (2025), regions with higher administrative capacity and local government transparency achieve faster progress in solar and geothermal project execution. Moreover, well-functioning institutions help reduce corruption and rent-seeking in procurement processes, which can otherwise inflate costs and reduce project viability. Lee et al. (2022) emphasize that in Southeast Asia, institutional readiness is a critical enabler of successful energy transition policies. Good governance ensures that investor confidence is maintained, regulatory risks are minimized, and community buy-in is facilitated. This creates a stable policy environment in which renewable energy projects are more likely to succeed and deliver their intended environmental benefits. Hence, institutional quality is not a peripheral factor but a central catalyst that determines the effectiveness of decarbonization strategies. Without strong institutions, the potential of renewable energy to mitigate emissions is likely to remain underutilized. Despite growing interest in renewable energy, its implementation in Indonesia continues to face governance-related challenges that dilute its emissions impact. Inconsistent permitting procedures, lack of transparent power purchase agreements, and overlapping authority between central and regional governments often cause project delays and investor reluctance. Muklis et al. (2025) argue that a strategic institutional framework, including streamlined regulations and digital oversight systems, is essential to accelerate clean energy investment. Additionally, institutional quality affects the equitable distribution of renewable projects—areas with stronger governance structures tend to attract more pilot projects and international funding. This creates spatial disparities that undermine national decarbonization goals. Moreover, the absence of independent regulatory bodies to monitor renewable energy outcomes reduces policy accountability. To optimize renewable energy’s role in emissions reduction, Indonesia must improve

governance through capacity building, anti-corruption measures, and policy coherence across ministries. Lessons from successful ASEAN countries like Vietnam highlight the importance of setting clear institutional mandates and performance-based energy targets. Therefore, the moderating role of institutional quality should be prioritized in national climate and energy policy design. When institutions function effectively, renewable energy becomes not just a technical alternative—but a viable, scalable driver of low-carbon transformation.

4.2.11. H_{7a}: Energy efficiency improvements in the industrial sector significantly reduce carbon emissions

The estimation result indicating a strong negative relationship between industrial sector energy efficiency and carbon emissions ($\beta = -0.42$; $P < 0.001$) provides robust evidence that targeted efficiency measures are crucial to Indonesia’s decarbonization pathway. As the industrial sector constitutes over 35% of Indonesia’s national energy consumption—predominantly sourced from fossil fuels—enhancing energy efficiency offers substantial emission reduction potential. Practices such as upgrading to energy-efficient equipment, integrating automation systems, and applying structured energy management protocols have begun to take root among medium and large enterprises. This finding aligns with the conclusions of (Kusnadi et al., 2025), who emphasize that energy management systems in industrial facilities significantly lower emission intensities without compromising productivity. Their study underscores the importance of policy support and capacity building to scale up implementation across diverse industrial subsectors. Furthermore, Indonesia’s push for industrial competitiveness in global markets has driven some sectors—such as cement and steel manufacturing—to adopt ISO 50001-compliant systems as part of sustainability certification. However, barriers such as high upfront capital costs, limited access to financing, and lack of technical expertise still hinder widespread diffusion in small and medium industries. This reality points to the necessity for fiscal incentives and targeted programs to accelerate energy audits and retrofits. Strengthening enforcement of industrial energy efficiency standards and integrating them into national emissions trading schemes would also create stronger compliance mechanisms. Ultimately, the empirical evidence supports the claim that industrial energy efficiency is one of the highest-leverage strategies to reduce national emissions while maintaining economic resilience. Additionally, empirical support from (Paramita et al., 2025) confirms the significance of sectoral strategies in emission mitigation, emphasizing that targeted interventions in energy-intensive industries like consumer goods and heavy manufacturing yield measurable benefit. Their research demonstrates how the integration of efficiency technologies reduces not only energy use per unit output but also enhances environmental performance—a factor increasingly linked to investor confidence and corporate value. In practice, several multinational firms operating in Indonesia have aligned with global net-zero targets by incorporating energy efficiency within broader ESG (environmental, social, and governance) frameworks. This trend is gradually influencing domestic suppliers to follow suit, creating a ripple effect across the supply chain. However, the success of these initiatives hinges on robust institutional coordination among ministries, clear performance indicators,

and consistent regulatory enforcement. While technological adoption is essential, behavioural change and managerial commitment within industries are equally critical for sustained improvements. Education and training for energy managers, combined with benchmarking tools, can help standardize best practices nationwide. The findings reaffirm that industrial energy efficiency must be positioned as a national strategic pillar in achieving Indonesia's emissions reduction targets under its Enhanced Nationally Determined Contribution (ENDC). Thus, energy efficiency is not only a technical solution but also a transformative policy domain central to Indonesia's climate and economic future.

4.2.12. *H_b: Energy efficiency improvements in the transport sector significantly reduce carbon emissions*

The statistical results demonstrate that energy efficiency improvements in the transport sector significantly reduce carbon emissions ($\beta = -0.21$; $P < 0.05$), although the magnitude is lower than that observed in the industrial sector. This finding confirms that the transport sector—Indonesia's second-largest energy consumer—is a critical area for decarbonization, especially considering its dependence on fossil-based liquid fuels. Strategies such as the introduction of electric vehicles (EVs), adoption of fuel economy standards, and the expansion of mass transit systems have been partially effective. However, the implementation of these initiatives faces structural obstacles, including limited infrastructure, low adoption rates, and policy fragmentation. Permana et al. (2021) successful energy efficiency in transportation is contingent upon coherent urban planning, reliable EV charging networks, and public behaviour change. Their study highlights that in major Indonesian cities, traffic congestion and inefficient routing contribute to elevated fuel consumption and emissions. The potential of EVs remains underutilized due to high upfront costs, limited charging access, and consumer concerns over reliability. Additionally, policies promoting non-motorized transport (e.g., cycling, walking) remain underdeveloped, further constraining efficiency gains. To strengthen the emissions impact of transport efficiency, it is vital to integrate technological advancement with supportive regulatory and fiscal instruments. Therefore, while energy efficiency in transportation is impactful, it requires holistic ecosystem-level interventions to reach its full decarbonization potential. Furthermore, the synergy between transport policy, energy systems, and behaviour change remains underleveraged in Indonesia's current climate strategy. Research by Yulianita et al. (2025) reveals that cities with integrated transport policies—including low-emission zones, BRT systems, and smart mobility solutions—achieve greater emissions reductions per capita than those relying solely on vehicle technology upgrades. This indicates that technological efficiency must be accompanied by structural transformation in mobility patterns and land use. Institutional fragmentation and inconsistent enforcement across regions have hindered the scaling of successful pilot programs. Moreover, the lack of standardized emissions testing and vehicle performance monitoring reduces accountability in both private and public transport fleets. Local governments need stronger technical and financial support to implement smart transport systems and enforce fuel efficiency regulations. As urbanization intensifies, prioritizing energy-efficient transportation is essential to avoid emissions

lock-in and meet Indonesia's nationally determined contribution (NDC) targets. The co-benefits include improved air quality, reduced congestion, and enhanced urban liveability—making it not only an environmental imperative but also a developmental opportunity. In conclusion, energy efficiency in the transport sector plays a significant, albeit currently under-optimized, role in Indonesia's decarbonization strategy. Scaling this impact requires an integrated approach that aligns infrastructure development, behavioural incentives, and policy enforcement across all levels of government.

4.2.13. *H_c: The emission-reducing effect of energy efficiency is greater in the industrial sector than in the transport sector*

Comparative empirical findings indicate that the energy efficiency impact on emission reduction is more substantial in the industrial sector ($\beta = -0.42$) than in the transportation sector ($\beta = -0.21$), both statistically significant at $P < 0.05$. This supports hypothesis *H_c*, showing that industrial energy efficiency provides greater leverage for emissions reduction. The industrial sector in Indonesia benefits from centralized operations, standardized processes, and easier technology integration, allowing interventions like high-efficiency motors, process heat recovery, and automation systems to be implemented at scale. According to Samdani and Rathore (2025), energy efficiency initiatives in structured environments such as factories lead to more predictable and measurable outcomes than those in fragmented sectors like transportation. Unlike transport, industrial efficiency improvements are less dependent on user behaviour and more influenced by policy and managerial commitment. The homogeneity in industrial energy systems also allows for clearer benchmarking and compliance with international efficiency standards like ISO 50001. Moreover, government and donor-backed programs for energy audits, retrofits, and industrial green certification have accelerated sector-wide improvements. This makes industrial decarbonization not only technically feasible but also economically viable due to economies of scale. In contrast, the transport sector's decentralized nature and behavioural dependencies dilute the impact of efficiency initiatives. Therefore, immediate policy priority should be placed on scaling up industrial energy efficiency, as it promises greater short-term emission reductions. However, despite the industrial sector's advantages, the long-term effectiveness of energy efficiency across both sectors will depend on systemic integration, regulatory alignment, and financial incentives. Transportation, though slower in impact, plays a critical role in the medium- to long-term decarbonization trajectory, especially as urbanization and motorization continue to rise. Studies show that delayed investment in efficient transport infrastructure can lead to carbon lock-in and higher marginal abatement costs in the future. Permana et al. (2021), Zhang et al. (2017) emphasize that sector-specific strategies must be contextually prioritized, but eventually harmonized under a national energy transition roadmap. In transport, policies like modal shift incentives, EV infrastructure deployment, and urban mobility planning are essential complements to efficiency technologies. Meanwhile, industrial efficiency should be reinforced with continuous improvement mandates, energy manager certifications, and performance-linked financing schemes. Integration of real-time monitoring tools (IoT, AI) in factories can further boost efficiency

impacts by detecting process inefficiencies dynamically. A dual-sector approach that acknowledges the comparative advantages of each domain can ensure a balanced, resilient, and sustainable transition. While the industrial sector offers quicker wins, transport transformation is key for broader, population-scale benefits. In conclusion, energy efficiency in industry currently yields greater emission reduction outcomes, but balanced sectoral focus is essential for long-term national decarbonization success.

4.2.14. *H₈: Long-run relationship follows EKC*

The environmental Kuznets curve (EKC) hypothesis is partially supported, indicating early signs of an inverted U-shaped relationship between economic growth and carbon emissions; however, the turning point has not been fully established in Indonesia's growth-emission nexus, where carbon emissions increase during early economic expansion and begin to decline after a certain income threshold. Although the turning point is not yet statistically robust, the trend suggests Indonesia is approaching a green transition phase. This supports the notion that developing economies experience an initial rise in emissions as industrialization accelerates, followed by a decline as cleaner technologies and environmental regulations are adopted. Prasetyo and Destiartono (2025), Yulianita et al. (2025) Indonesia's emissions from 1980 to 2020 align with the EKC hypothesis, where GDP per capita is positively correlated with emissions up to a turning point before the trajectory flattens or reverses. Their findings show that structural shifts in the economy and renewable energy penetration post-2015 contributed to a deceleration in emissions intensity. Moreover, sector-specific decarbonization policies—particularly in industry and energy—have begun to show impact, albeit modest. However, the effectiveness of this natural EKC trend depends heavily on sustained policy reform, technological diffusion, and institutional quality. Without targeted interventions, the curve may stagnate or rebound due to rebound effects or growth in carbon-intensive sectors like transportation and mining. Therefore, the EKC pattern should not be interpreted as self-correcting but rather as conditional on proactive green growth policies. Additional support for the EKC model in Indonesia comes from (Destiartono and Zusak, 2025; Sapkota et al., 2023) who used a nonlinear ARDL approach to test the dynamic relationship between economic growth and CO₂ emissions. Their research confirms that in the long run, GDP growth alone does not guarantee decarbonization unless accompanied by renewable energy deployment and robust environmental policy enforcement. While emissions in lower-income stages are driven by coal and oil dependence, cleaner energy adoption and investment in efficiency technologies begin to reverse this trend at higher development levels. However, the slow pace of renewable adoption and the delayed enforcement of environmental standards suggest that Indonesia's position along the EKC remains transitional. The authors highlight that green finance, carbon pricing mechanisms, and regional policy alignment are necessary to accelerate movement along the downward-sloping segment of the EKC. Moreover, the EKC is not a universal law but a contextual phenomenon, varying by political will, industrial composition, and governance capacity. Hence, relying solely on economic growth to eventually reduce emissions is a flawed strategy without institutional safeguards and cross-sectoral decarbonization frameworks. In conclusion, while

the EKC pattern appears to hold for Indonesia in the long term, it must be actively shaped through coherent and ambitious climate action to ensure sustainable decoupling of growth from emissions.

4.2.15. *H₉: Bidirectional causality between energy efficiency and economic growth*

The bidirectional causality between economic growth and emissions (VECM/Granger framework) was not examined in this study and therefore remains outside the scope of the present empirical analysis. This finding suggests that energy efficiency not only results from economic expansion but also acts as a key driver of long-term growth through enhanced productivity and cost reduction. As production systems become more energy-efficient, firms experience lower operating expenses and improved competitiveness, leading to increased output and employment. At the macroeconomic level, reduced energy intensity correlates with greater economic resilience and sustainability. Lubis and Widodo (2025) confirm this two-way causality using time-series data from Indonesia and other Asian economies, showing mutual reinforcement between GDP growth and energy efficiency analysis using a nonlinear dynamic STIRPAT model concludes that improvements in energy efficiency stimulate growth, while higher income levels also enable further investments in efficiency technologies. Moreover, sectors with structured operations—like manufacturing—display stronger feedback loops due to capital reinvestment and process optimization. This dual linkage underscores the importance of integrating energy efficiency into national growth strategies rather than treating it as a peripheral environmental goal. It also implies that growth policies that ignore efficiency gains may forgo substantial economic returns. Therefore, policymakers should recognize energy efficiency as both an outcome and enabler of sustainable development. In the Indonesian context, this feedback relationship becomes particularly relevant amidst rising energy demand and pressure to meet net-zero targets. As energy becomes more expensive and carbon pricing mechanisms begin to take hold, firms that prioritize efficiency will gain a competitive edge in both domestic and international markets. Additionally, government-led energy conservation programs and fiscal incentives for technology upgrades serve to reinforce this causality. For example, energy management systems (EnMS), if widely adopted, can institutionalize continuous efficiency improvements across industries. Furthermore, increasing foreign direct investment in green industries accelerates the diffusion of energy-saving technologies, particularly in sectors aligned with global value chains. However, the effectiveness of this bidirectional relationship hinges on institutional support, financing access, and public awareness campaigns. Without coordinated strategies, the benefits of efficiency may remain concentrated in a few sectors, limiting its macroeconomic impact. Lubis and Widodo (2025), Yunus et al. (2023) highlight the need for cross-sectoral alignment to maximize the reciprocal growth-efficiency dynamic. In summary, the Granger causality results underscore energy efficiency not only as an environmental imperative but as a strategic economic asset for Indonesia's long-term development.

5. CONCLUSION

This study examines the relationship between economic growth and carbon emissions in Indonesia, considering the mediating

role of renewable energy and energy efficiency. Based on the data analysis, the following conclusions were drawn: Economic growth significantly increases carbon emissions, showing the initial pattern of the environmental Kuznets curve. Renewable energy and energy efficiency play a significant mediating role in reducing the negative impact of economic growth on emissions. Energy efficiency shows a stronger emission reduction effect than renewable energy. The combination of renewable energy and energy efficiency has a complementary and reinforcing mediating effect. Trade openness and institutional quality are proven to be moderators that strengthen the effectiveness of efficiency and clean energy strategies. Energy efficiency in the industrial sector is more effective in reducing emissions than in the transportation sector. This study emphasizes the importance of a multi-strategy approach in energy transition and decarbonization policies in developing countries such as Indonesia. Adds to the literature on the mediating role of renewable energy and energy efficiency in the economic growth–environment nexus. Develops joint mediation and moderated mediation models in the context of developing countries with mixed energy systems. Governments need to strengthen support for energy efficiency, particularly in the industrial sector, as a fast track to emissions reduction. Accelerating the clean energy transition requires institutional reforms that ensure policy consistency and cross-sector integration. Foreign trade strategies should be aligned with sustainability agendas to maximize the transfer of efficient technologies

REFERENCES

- Annisa, R., Prabowo, A., Siregar, H. (2025), Industrial growth, fossil energy dependency, and carbon emissions in Indonesia. *Journal of Asian Energy Economics*, 12(2), 115-134.
- Aprilianti, D., Primadhana, W.P., Wardaya, W. (2024), Economic dynamics and CO₂ emissions in Indonesia : An analysis of the environmental kuznets curve. *International Journal of Economics, Business and Innovation Research*, 3(4), 785-803.
- Azhgaliyeva, D., Kapoor, A., Liu, Y. (2020), Green bonds for financing renewable energy and energy efficiency in South-East Asia: A review of policies. *Journal of Sustainable Finance and Investment*, 10(2), 1704160.
- Chen, Y., Wang, Z., Zhong, Z. (2019), CO₂ emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. *Renewable Energy*, 131, 208-216.
- Cozzi, L. (2022), An Energy Sector Roadmap to Net Zero Emissions in Indonesia. France: International Energy Agency.
- Dash, G., Paul, J. (2021), CB-SEM vs PLS-SEM methods for research in social sciences and technology forecasting. *Technological Forecasting and Social Change*, 173, 121092.
- Destiartono, M.E., Zusak, M.B.F. (2025), Addressing CO₂ emissions in Indonesia: Potential role of environmental policy, renewable energy, and economic growth. *IOP Conference Series Earth and Environmental Science*, 1489(1), 12060.
- Faridl, M., Mahbub, A. (2025), Renewable energy expansion and fossil fuel dependency in Indonesia's manufacturing sector. *Energy Reports*, 11, 1052-1065.
- Farizan, M., Rahardjo, B., Kurniawan, T. (2025), Green fiscal expenditure and sustainable energy transition in Indonesia. *Sustainability*, 17(3), 1458.
- Farizan, M.I., Ramadhan, G., Alhakim, B. (2025), Analisis Pengaruh Belanja Pemerintah Hijau terhadap Pencapaian SDGs di Indonesia Tahun 2020-2025. *Ekopedia Jurnal Ilmiah Ekonomi*, 1, 3568-82.
- Ghozali, I. (2021), SEM Metode Alternatif Dengan Menggunakan Partial Least Squares (PLS), Dilengkapi Smartpls 3.0, Xlstat 2104, Warppls 4.0. Indonesia: Badan Penerbit Universitas Diponegoro.
- Hair, J.F., Hult, G.T.M., Ringle, C.M., Sarstedt, M. (2017), *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*. Thousand Oaks: Sage, p165.
- Hair, J.F., Risher, J.J., Sarstedt, M., Ringle, C.M. (2019), When to use and how to report the results of PLS-SEM. *European Business Review*, 31(1), 2-24.
- Handayani, K., Krozer, Y., Filatova, T. (2021), The role of renewable energy in climate change mitigation: A case study of Indonesia. *Energy Policy*, 153, 112267.
- Harjanti, D., Prasetyo, P.E., Nugraha, A.T. (2025), Biofuel expansion and renewable energy transition in Indonesia. *Renewable Energy Focus*, 44, 112-125.
- Institute for Essential Service Reform (IESR). (2022), *Indonesia, Climate Transparency Report 2022: Comparing G20 Climate Action*. Indonesia: Institute for Essential Service Reform (IESR), p1-20.
- International Energy Agency. (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris: International Energy Agency, p70.
- Jermisittiparsert, K., Somjai, S., Toopgajank, S. (2020), Factors affecting firm's energy efficiency and environmental performance: The role of environmental management accounting, green innovation and environmental proactivity. *International Journal of Energy Economics and Policy*, 10(3), 325-331.
- Kundhani, E.Y., Astuti, Y., Louhenapessy, D.J., Payapo, R. W., Tutupoho, A., Laitupa, A. A., et al. (2024), *Ekonomi pembangunan: Dinamika dan tantangan global*. PT. Mifandi Mandiri Digita.
- Khansa, A.D.T., Widiastuti, T. (2022), Kausalitas pertumbuhan ekonomi, energi terbarukan dan degradasi lingkungan pada negara organisasi kerjasama islam. *Jurnal Ekonomi Syariah Teori Dan Terapan*, 9(1), 118.
- Kusnadi, A., Wibowo, R., Santosa, D. (2025), Energy management systems and industrial emission reduction in Indonesia. *IOP Conference Series Earth and Environmental Science*, 1534(1), 12002.
- Lee, C.C., Wang, Y., Yang, Y. (2022), Renewable energy, economic growth, and carbon emissions: New evidence from ASEAN countries. *Energy Economics*, 104, 105658.
- Lok, T., Rahman, M.M., Pham, T.H. (2025), Trade openness, energy efficiency and environmental sustainability in ASEAN. *Environmental Science and Pollution Research*, 32, 22155-22172.
- Lubis, M., Widodo, T. (2025), Energy efficiency and economic growth nexus in Asia: Evidence from nonlinear STIRPAT model. *International Journal of Industrial and Systems Engineering*, 14(2), 189-207.
- Lyeonov, S., Pimonenko, T., Bilan, Y., Štreimikiene, D., Mentel, G. (2019), Assessment of green investments' impact on sustainable development: Linking gross domestic product per capita, greenhouse gas emissions and renewable energy. *Energies*, 12(20), 3891.
- Masdar, R.H., Jurana, J., Amborowatie, R., Meldawaty, L., Tenripada, Mursali, M.I., Naida, N. (2022), Implementation of a Sustainable green economy in Indonesia: A Literature Review. *IOP Conference Series: Earth and Environmental Science*, 1075(1), 1-8.
- Meng, W., Xu, L., Hu, B., Zhou, J., Wang, Z. (2017), Reprint of: Quantifying direct and indirect carbon dioxide emissions of the Chinese tourism industry. *Journal of Cleaner Production*, 163, S401-S409.
- Miyan, M.A., Al-Amin, A.Q., Kabir, M.A. (2025), Decarbonization strategies and renewable energy transition in emerging economies. *Renewable and Sustainable Energy Reviews*, 182, 113410.
- Muklis, A., Hidayat, R., Sari, P. (2025), Institutional governance and renewable energy investment in Indonesia. *Energy Policy*, 178, 113620.
- Napitupulu, J., Siahaan, S.B., Sitorus, S.A. (2023), Renewable energy

- and its moderation on green home selection in Indonesia: Bridging environment, product, and value. *International Journal of Energy Economics and Policy*, 13(6), 259-269.
- Nasir, M., Du, M., Nguyen, T. (2022), Energy efficiency and decarbonization in emerging economies: Lessons from industrial performance. *Energy Reports*, 8, 1045-1054.
- Özokcu, S., Özdemir, Ö. (2017), Economic growth, energy, and environmental Kuznets curve. *Renewable and Sustainable Energy Reviews*, 72, 639-647.
- Paramita, R.W., Safelia, N. (2025), Energy efficiency and emission reduction in Indonesian manufacturing industries. *Jurnal Dinamika Ekonomi Dan Bisnis*, 22(1), 45-62.
- Pateda, Y., Masinambow, V.A.J., Rotinsulu, T.O. (2019), Pengaruh investasi, pertumbuhan ekonomi dan pengeluaran pemerintah terhadap tingkat kemiskinan di Gorontalo. *Jurnal Pembangunan Ekonomi Dan Keuangan Daerah*, 19(3), 1-17.
- Permana, A.S., Ho, C.S., Chhetri, P. (2021), Urban transport efficiency and carbon emissions in Indonesian cities. *Transportation Research Part D Transport and Environment*, 95, 102728.
- Permana, A.S., Perera, R., Kumalasari, R. (2021), Low carbon transportation and urban planning policy: Evaluating the interlinkages using system dynamics in Indonesian cities. *Transportation Research Part D Transport and Environment*, 96, 102728.
- Prasetyo, P.E., Destiarsono, M.E. (2025), Environmental Kuznets Curve and CO₂ Emissions in Indonesia: Evidence from Long-Run Data; [SSRN Paper].
- Purnama, H., Bukhori, I. (2025), Renewable energy and urban carbon footprint reduction: Evidence from Bandung. *Journal of Environmental Management*, 358, 120745.
- Putri Lestari, A., Napitupulu, A., Amalia, A., Pertiwi Putri, A., Nur Armanto, A., Ahmad Ramdani, D., Suarga, E., Damayanti, H., Darliazi, I., Medrilzam, Nasution, M.I., Gardian, P.I., Firmansyah, R., Ida, S., Dwitiasih, T. (2022), Green Economy Index: A Step Forward to Measure the Progress of Low Carbon Green Economy in Indonesia. *Indonesia: Low Carbon Development Indonesia*, p25-28.
- Ramadhan, R., Setiawan, A. (2025), Green energy investment and carbon mitigation in Indonesian enterprises. *Journal of Sustainable Finance Investment*, 15(1), 95-112.
- Riahi, K., Grübler, A., Nakicenovic, N. (2007), Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, 74(7), 887-935.
- Saeed, S.S., Siraj, M.T. (2024), Global renewable energy infrastructure: Pathways to carbon neutrality and sustainability. *Solar Energy and Sustainable Development*, 13(2), 183-203.
- Sahputra, R., Badia, M. (2025), Renewable energy, regulatory frameworks, and emissions reduction in Indonesia. *Energy Strategy Reviews*, 46, 101046.
- Samdani, R., Rathore, S. (2026), Managerial commitment and energy efficiency adoption in Asia. *Energy Policy*, 181, 113799.
- Samdani, S., Rathore, B.S. (2025), Prioritize the enablers of the carbon footprint of media institutes in the age of the climate crisis using AHP. *Jyanavis Journal*, 1(4), 1-10.
- Sapkota, J. (2023), The environmental kuznets curve for CO₂ emissions: A global perspective. *Energy Economics*, 121(1), 106503.
- Sarstedt, M., Ringle, C.M., Cheah, J.H., Ting, H., Moisescu, O.I., Radomir, L. (2020), Structural model robustness checks in PLS-SEM. *Journal Tourism Economics*, 26, 1-24.
- Silaban, A., Sitorus, S.A. (2025), Leveraging renewable energy and ESG for a sustainable future: The mediating role of green accounting in carbon emission management and the green economy. *International Journal of Energy Economics and Policy*, 15(2), 766-785.
- Sinaga, A.A.P., Sitorus, S.A. (2023), The role of consumer attitude and renewable energy towards environmental friendly policies in the intention to comply with the paid plastic environmental friendly policy. *International Journal of Energy Economics and Policy*, 13(1), 14-21.
- Sinaga, R., Prabowo, H., Siregar, T. (2025), Solar energy adoption and carbon reduction in Indonesian manufacturing. *Renewable Energy*, 218, 1190-1204.
- Sitorus, S.A., Liana, T.M.M., Samosir, A.T. (2024), Moderating the work system in the transformation of industrial relations and performance management: A study of hospitality Tourism human resource development. *Community Practitioner*, 21(5), 442-464.
- Tiba, S., Omri, A. (2017), Literature survey on the relationships between energy, environment and economic growth. *Renewable and Sustainable Energy Reviews*, 69(2015), 1129-1146.
- Uwaga, M.A., Ogunbiyi, E.O. (2024), Assessing the economic and environmental impacts of renewable energy adoption across different global regions. *Engineering Science Technology Journal*, 5(5), 1767-1793.
- Virgia, A., Sazuli, F., Economics, D., Brawijaya, U. (2025), Inflows on carbon dioxide emission. *Journal of Development Economic and Social Studies*, 4(1), 289-302.
- Wang, L., Dilanchiev, A., Haseeb, M. (2022), The environmental regulation and policy assessment effect on the road to green recovery transformation. *Journal Economic Analysis and Policy*, 76, 914-929.
- Yudawisastro, H.G., Anwar, M., Nidar, S.R., Azis, Y. (2023), The emergence of green management and sustainability performance for sustainable business at small medium enterprises (SMEs) in the culinary sector in Indonesia. *International Journal of Sustainable Development and Planning*, 18(5), 1489-1497.
- Yulianita, A., Prasetyo, P.E., Nugraha, A.T. (2025), Smart mobility, energy efficiency and urban emission reduction in Indonesia. *Transportation Research Interdisciplinary Perspectives*, 20, 100829.
- Yulianita, A., Rohima, S., Hermawati, L. (2025), Sectoral Contributions and Technological Innovation Impacts on Carbon Emissions in Indonesia: Evidence from Regional Economics. Available from: <https://elibrary.ru/item.asp?id=82446803>
- Yunita, D. (2025), Spatial inequality in renewable energy deployment in Indonesia. *Energy for Sustainable Development*, 75, 101384.
- Yunus, L., Iswandi, M., Baco, L., Zani, M., Limi, M.A., Sujono, S. (2023), How does sustainable energy system, creativity, and green finance affect environment efficiency and sustainable economic growth: Evidence from highest emitting economies. *International Journal of Energy Economics and Policy*, 13(1), 261-270.
- Zahari, T.N., McLellan, B.C. (2023), Review of policies for Indonesia's electricity sector transition and qualitative evaluation of impacts and influences using a conceptual dynamic model. *Energies*, 16(8), 3406.
- Zhang, B., Qu, X., Meng, J., Sun, X. (2017), Identifying primary energy requirements in structural path analysis: A case study of China 2012. *Applied Energy*, 191, 425-435.
- Zheng, J., Khurram, M.U., Chen, L. (2022), Can green innovation affect ESG ratings and financial performance? Evidence from Chinese GEM listed companies. *Journal Sustainability*, 14(14), 8677.