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Research Article

Advancing Sustainable Energy Transitions in ASEAN Through Green Innovation, Technological Advancement, and Economic Freedom: Evidence from Panel ARDL Modeling

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Abstract

This research investigates the impact of green and technological innovations, and economic freedom on the utilization of sustainable energy in ASEAN countries over the period from 1995 to 2023. Employing panel ARDL (Autoregressive Distributed Lag) modeling in EViews, the study explores these variables' dynamic and long-term relationships. The results demonstrate that green innovation significantly and positively affects sustainable energy utilization, underscoring the critical role of environmentally friendly technological advancements in enhancing energy sustainability. Technological innovations and economic freedom also exhibit positive associations with sustainable energy adoption, indicating that technological advancements and a liberal economic environment contribute to the increased use of renewable energy sources. The findings highlight that ASEAN countries must prioritize green innovation-oriented policies that can effectively drive sustainable energy utilization. These countries can support institutional green development and foster a more sustainable energy landscape by translating green innovations into practical applications. Additionally, the findings emphasize the importance of directing economic growth capital towards sustainable energy projects. This can be achieved by expanding and reforming existing policies to better align with sustainable development goals. The research provides several important recommendations for policymakers in the ASEAN region.

Keywords: Green Innovation, Technological Innovation, Economic Freedom, Sustainable Energy, ASEAN, Panel ARDL Modeling

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1 INTRODUCTION

The quality of life increasingly depends on a reliable supply of renewable energy that is derived from inexhaustible natural sources such as wind, biomass, solar activity, and geothermal power in ways considered sustainable. The high reliance on renewable energy sources provides a better cushion to fall back upon in the wake of fossil energy market-related crises. The relationship between the consumption of sustainable energy, monetary progress, and economic growth has been logically inferred from previous research findings (Asif et al., 2024; Isiksal & Assi, 2022; Qingquan et al., 2020). According to the goals outlined by the United Nations, environmental sustainability (SDG 13) and economic growth (SDG 8) are the two most challenging objectives for developing nations. Thus, immediate action is required from governments in the form of green policies and regulatory frameworks (Alola et al., 2022; Han et al., 2025). The importance of preserving the environment necessitates specific actions that can reduce carbon emissions and greenhouse gases. This can be achieved by diminishing the reliance on fossil fuels and other non-renewable forms of energy (Liu et al., 2022). The harnessing of clean and renewable energy sources promotes sustained economic development by minimizing potential harmful effects on the environment. In contrast, economic development will decline due to the depletion of natural resources; consequently, regulatory bodies, such as the Kyoto Agreement, must act as the driving force and encourage the consumption of green energy resources among the public (Aydin et al., 2024; Sun et al., 2019).

Green innovation is a critical factor in preserving the environment and promoting economic growth, as it involves adopting eco-friendly technologies and optimizing energy efficiency (Sun et al., 2019; Zheng et al., 2021). In countries like those in the Association of Southeast Asian Nations (ASEAN), where industrial activities are rapidly increasing and the adverse effects of climate change are becoming more visible (Li et al., 2023), integrating green innovation with pollution-preventive practices is especially important. Despite the numerous benefits of transitioning to renewable energy sources, ASEAN countries have faced various challenges in implementing this change (Manal, 2025). These challenges include the region's heavy reliance on fossil fuels, the varying levels of economic development and institutional quality, and the financial limitations that prevent sustainable energy investments. In many ASEAN countries, the financial system is still in its nascent stages and cannot support the financing of sustainable energy initiatives (Ofori et al., 2023). Moreover, technological innovation, which is crucial for effectively utilizing renewable energy, is not uniformly distributed throughout the region. The disparities in economic freedom, which impact market openness, regulatory quality, and ease of doing business, also influence the extent to which ASEAN nations can embrace and benefit from sustainable energy (Amir et al., 2025; Chandratreya, 2025).

Earlier research indicated the significant roles green and technological innovation play in encouraging the use of sustainable energy. A gap remains in understanding how such factors interact with economic freedom to affect renewable energy adoption in the ASEAN. Given the unique social, economic, and political landscape of the region, these are dynamics that will need in-depth investigation (Feng et al., 2024). Green innovation improves sustainable energy use by improved resource allocation and reduced capital cost, while technological innovation promotes renewable energy with enhanced efficiency and cost reduction (Feng et al., 2024; Ofori et al., 2023; Rehman Khan et al., 2023; Sun et al., 2019). Economic freedom, through issues of property rights, free trade, and regulatory efficiency, provides an enabling environment for financial development and technological innovation (Manal, 2025; Ofori et al., 2023).

This research examines the impact of economic freedom, green and technological innovations on sustainable energy use in the ASEAN countries. The study's essential findings and contributions towards policy and strategy decision-making by the ASEAN countries are significant. It establishes a foundation for policymakers to design targeted interventions by understanding the interplay between the green and technological capabilities, and economic freedom in achieving sustainable energy (Saqib et al., 2024). The research also adds to the existing literature by focusing on the ASEAN region, where the nexus among these variables has not been exhaustively examined using advanced econometric techniques. This will aid in harmonizing national policies with international commitments, such as the SDGs and the Paris Agreement, on the critical role of renewable energy in sustainable development. Furthermore, the study provides broader implications for economic and environmental sustainability (Pata, 2025; Shaukat et al., 2023). Drawing upon the insights from such research, policy implications that inform sustainable energy practices without compromising economic development can be derived as ASEAN strives towards clean and green development. The study's emphasis on green and technological variables underscores the need for comprehensively addressing the diversified dimensions of sustainable energy (Chandratreya, 2025). This research aligns well with international trends towards reducing greenhouse gas emissions and mitigating climate change through green innovation and pollution prevention.

2 LITERATURE REVIEW

The relationship between green innovation, technological innovation, economic freedom, and sustainable energy is multifaceted and intricate as remain point of discussion in literature (Amir et al., 2023; Asif et al., 2024; Feng et al., 2024; Ockwell & Byrne, 2016; Rennings, 2000; Sun et al., 2019; Zheng et al., 2021). As Rennings (2000) highlights, green innovation is of paramount importance in achieving environmental goals, possessing the potential to drive the adoption of renewable energy technologies. According to Horbach (2008), there exists a positive correlation between green innovation activities and the adoption of renewable energy sources in the German manufacturing sector, indicating that companies actively engaged in green innovation are more likely to invest in sustainable energy technologies(Wang et al., 2025). In a similar vein, Costantini and Mazzanti (2012) utilizing panel data from European countries, show that policy-driven green innovations, such as subsidies and tax incentives for renewable energy projects, effectively increase the share of sustainable energy in the energy mix. Carrión-Flores and Innes (2010) further elucidate those environmental regulations, which stimulate green innovation, have a significant positive impact on renewable energy adoption (Carrión-Flores & Innes, 2010; Han et al., 2025; Isiksal & Assi, 2022; Qingquan et al., 2020).

While technological innovation is a crucial factor in advancing renewable energy technologies, improving grid infrastructure, and enhancing energy storage solutions, Assi et al. (2020) emphasizes the importance of technological innovation as a key driver of energy transitions. According to Assi et al. (2020) advancements in renewable energy technologies, such as solar panels and wind turbines, play a crucial role in increasing the share of sustainable energy. Hye et al. (2023) analyze patent data across multiple countries and find a strong correlation between technological innovation in the renewable energy sector and increased investment in and deployment of sustainable energy technologies. Ma et al. (2024) using data from China, demonstrate that technological innovations in energy storage and grid management significantly enhance the efficiency and reliability of renewable energy systems, leading to higher adoption rates of sustainable energy. Furthermore, Lee and Min (2015) provide evidence from South Korea, showing that technological innovations in energy-efficient technologies make a significant contribution to sustainable energy outcomes (Carrión-Flores & Innes, 2010; Chandratreya, 2025; Horbach, 2008; Hye et al., 2023; Shaukat & Ali, 2023).

Economic freedom, as defined by institutions such as the Heritage Foundation, plays a critical role in promoting sustainable energy (Pata, 2025; Shaukat et al., 2023). This is characterized by the absence of excessive government intervention, secure property rights, open markets, and efficient regulation. Research has shown a positive relationship between economic freedom and renewable energy consumption. Costantini and Mazzanti (2012) found that economic freedom fosters a favorable environment for investments in sustainable energy in a panel of developed and developing countries. Aydin et al. (2024) demonstrated that higher levels of economic freedom are associated with increased investments in renewable energy projects in MENA countries, as economic freedom reduces regulatory burdens and encourages private sector participation (Abbass et al., 2025). Vachon and Menz (2006) examined the impact of economic freedom on renewable energy policies in the United States and found that states with higher economic freedom are more likely to implement supportive policies for renewable energy development, leading to higher adoption rates of sustainable energy technologies (Bashiru et al., 2024; Gull et al., 2023). Furthermore, Ockwell and Byrne (2016) suggested that economic freedom enhances entrepreneurial activities, which are crucial for driving innovation and sustainable energy development.

In addition Iurchenko et al. (2024) explain that primary factors, control variables such as economic growth and capital formation are essential in understanding sustainable energy development (Bashiru et al., 2024). Economic growth, measured by GDP growth, reflects the overall economic performance of a country. Higher economic growth can lead to increased energy consumption, but it can also provide the financial resources needed to invest in renewable energy infrastructure. Studies by Sun et al. (2019) and Zheng et al. (2021) indicate a positive relationship between economic growth and renewable energy consumption. Capital formation, referring to the accumulation of capital assets such as machinery, infrastructure, and technology, is crucial for the development of energy infrastructure, including renewable energy projects. Acemoglu et al. (2012) highlight that capital formation plays a significant role in facilitating the transition to sustainable energy systems.

Hence, the empirical research demonstrates significant positive correlations between green innovation, technological innovation, economic freedom, and sustainable energy. Green innovation plays a key role in promoting the adoption of renewable energy technologies through environmentally friendly practices and products. Technological innovation enhances the efficiency and practicality of sustainable energy solutions, facilitating their integration into the energy mix (Abbass et al., 2025; Saqib et al., 2024). Economic freedom fosters a favourable environment for investments in sustainable energy by reducing regulatory barriers and encouraging private sector participation. These findings emphasize the importance of supporting green and technological innovations and promoting economic freedom to achieve sustainable energy development in ASEAN countries. Additionally, robust economic growth and capital formation are essential in providing the necessary resources and infrastructure for sustainable energy projects (Iurchenko et al., 2024; Kylili et al., 2025).

3 RESEARCH METHODS

This study focuses on ASEAN countries, specifically Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. These countries were selected due to their diverse stages of economic development, varying levels of technological advancement, and differing degrees of economic freedom, making them a suitable sample for examining the interplay between green innovation, technological innovation, economic freedom, and sustainable energy utilization. Penal data for the period from 1995 to 2023 were collected to provide a comprehensive view of these relationships over time. The ASEAN region is also experiencing rapid economic growth and industrialization, which makes the investigation of sustainable energy adoption particularly relevant and urgent.

3.1 Variables Measurement and Sources

Sustainable energy utilization (SEU) was measured as the percentage of total energy consumption derived from renewable sources, using data from Our World in Data (OWD) Indicators. Technological innovation (TIN) was assessed through the Technological Innovation Index obtained from the World Development Indicators (WDI), which reflects the development and application of new technologies. Green innovation (GIN) was measured using proxies such as the number of patents filed for environment-related technologies, also sourced from the WDI. Economic freedom (EF) was quantified using the Economic Freedom Index provided by the Heritage Foundation Indicators (HFI), which assesses the level of economic freedom based on regulatory efficiency, rule of law, and open markets. Additionally, economic growth (EG) was measured by the annual GDP growth rate, and capital formation (CF) was measured as gross fixed capital formation as a percentage of GDP, both sourced from the WDI. These measurements are supported by existing literature (Amir et al., 2023; Aydin et al., 2024; Costantini & Mazzanti, 2012; Isiksal & Assi, 2022; Ma et al., 2024; Rennings, 2000; Saqib & Usman, 2023), which have utilized similar proxies and indices to investigate these variables.

3.2 Model Selection Justification

The Autoregressive Distributed Lag (ARDL) model was chosen for this study due to its flexibility and suitability for small sample sizes and its ability to be applied irrespective of whether the underlying variables are I(0), I(1), or mutually cointegrated. The ARDL model allows for the examination of both short-term and long-term relationships between variables, making it an ideal choice for analyzing the dynamic interactions between green innovation, technological innovation, economic freedom, and sustainable energy utilization. The ARDL approach is well-suited for the diverse economic conditions present within ASEAN countries, enabling a nuanced understanding of how these variables interact over time. This choice is further justified by previous studies, such as those by Pesaran et al. (2001) and Narayan (2005), which have successfully employed the ARDL model in similar contexts.

3.3 Study Equation and ARDL Model

The study employs the following equation to analyze the relationships between the variables:

$$SEU_{it} = \alpha + \beta_1 GIN_{it} + \beta_2 TIN_{it} + \beta_3 EF_{it} + \beta_4 EG_{it} + \beta_5 CF_{it} + \epsilon_{it}$$

where SEU_{it} represents sustainable energy utilization in country (i) at time (t); GIN_{it} represents green innovation; TIN_{it} represents technological innovation; EF_{it} represents economic freedom; EG_{it} represents economic growth; and CF_{it} represents capital formation. The ARDL model examines both short-term and long-term relationships between the variables. The long-run equation models the steady-state relationship:

$$SEU_{it} = \alpha + \sum_{j=1}^{p} \delta_j SEU_{i,t-j} + \sum_{k=0}^{q} \beta_k GIN_{i,t-k} + \sum_{l=0}^{r} \gamma_l TIN_{i,t-l} + \sum_{m=0}^{s} \phi_m EF_{i,t-m} + \sum_{n=0}^{t} \theta_n EG_{i,t-n} + \sum_{o=0}^{u} \psi_o CF_{i,t-o} + \epsilon_{it}$$

The short-run equation captures the immediate effects and the error correction mechanism:

$$\Delta SEU_{it} = \alpha + \sum_{j=1}^{p} \delta_j \Delta SEU_{i,t-j} + \sum_{k=0}^{q} \beta_k \Delta GIN_{i,t-k} + \sum_{l=0}^{r} \gamma_l \Delta TIN_{i,t-l} + \sum_{m=0}^{s} \phi_m \Delta EF_{i,t-m} + \sum_{n=0}^{t} \theta_n \Delta EG_{i,t-n} + \sum_{o=0}^{u} \psi_o \Delta CF_{i,t-o} + \lambda ECT_{i,t-1} + \epsilon_{it}$$

where Δ denotes the first difference operator and λ is the coefficient of the error correction term (ECT), representing the speed of adjustment back to the long-run equilibrium. The error correction term $ECT_{i,t-1}$ is derived from the long-run equation. This model enables the investigation of how changes in green innovation, technological innovation, and economic freedom impact sustainable energy utilization in both the short and long term, while controlling economic growth and capital formation. This approach provides valuable insights into the factors driving sustainable energy development in ASEAN countries and helps inform policy decisions aimed at promoting green and technological innovations, enhancing economic freedom, and achieving sustainable energy goals.

4 EMPIRICAL FINDINGS AND DISCUSSION

Empirical findings reveal that establishing stationarity in the time series data is crucial as it ensures the reliability and validity of statistical analyses. Results using the Levin, Lin, and Chu (LLC) and Im, Pesaran, and Shin (IPS) tests underscore the importance of establishing stationarity, reinforcing the robustness of subsequent econometric modelling.

Table 1. ADF and LLC unit root

Constructs	IPS Test		LLC Test	
	Level	1st diff.	Level	1st diff.
SEU	-2.534*	-5.671**	-2.294*	-5.204**
GIN	-2.627*	-8.568**	-1.397	-6.244***
TIN	-1.376	-6.251**	-4.917*	8.229***
EF	-2.561*	-7.533***	-4.237*	-6.237***
EG	-2.271*	-2.917***	-2.371*	-6.499***
GCF	-2.261*	-6.446***	-1.361	-6.238***

Note. *SEU = Sustainable Energy Utilization; GIN = Green Innovation; TIN = Technological Innovation; EF = Economic Freedom; EG = Economic Growth; GCF = Gross Capital Formation. IPS = Im, Pesaran and Shin test; LLC = Levin, Lin and Chu test. All variables are stationary at first difference, indicating integration of order one (I(1). Significance levels: * = p < 0.10; ** = p < 0.05; *** = p < 0.01.* ***Source(s):*** *Authors' Own Work.*

Table 1 showing Sustainable Energy Utilization exhibits stationarity with significant results across both tests, confirming its stable behaviours over time without the presence of unit roots. Green Innovation shows stationarity after first differencing, evidenced by significant results in the LLC test for first difference, indicating its suitability for further econometric analysis despite potential non-stationarity at the level. Technological Innovation displays mixed results, with significant stationarity observed after differencing in the LLC test, suggesting its dynamic behavior in the short term. Economic Freedom demonstrates clear stationarity, with significant results at the 1% level for both level and first difference in the LLC test, highlighting its consistent influence on economic policies affecting SEU. Economic Growth and Capital Formation both exhibit stationarity after differencing, supported by significant results in the LLC test for first difference, indicating their impacts on sustainable energy outcomes over time.

The ARDL model results reveal significant relationships between the independent variables and Sustainable Energy Utilization in ASEAN countries, capturing both short-term dynamics and long-term equilibrium effects. In the long run, Green Innovation demonstrates a positive and statistically significant impact on SEU, with a coefficient of 0.313 (t-value = 3.648), indicating that advancements in green technologies contribute positively to sustainable energy adoption over time. Technological Innovation also shows a positive effect on SEU, although slightly less significant, with a coefficient of 0.182 (t-value = 2.462), emphasizing the role of technological advancements in promoting sustainable energy practices. Economic Freedom (EF) exhibits a significant positive impact on SEU, with a coefficient of 0.164 (t-value = 3.584), underscoring the importance of economic policies conducive to sustainable development. Economic Growth is found to positively influence SEU with a coefficient of 0.322 (t-value = 4.952), highlighting the role of economic expansion in driving sustainable energy utilization. However, Capital Formation does not show a significant impact in the long run, suggesting its influence may be less pronounced in the context of sustainable energy outcomes in ASEAN countries. In the short run, Green Innovation continues to exert a strong positive effect on SEU, with a coefficient of 0.349 (t-value = 4.583), indicating immediate benefits from innovative green technologies.

Technological Innovation and Economic Freedom also demonstrate significant short-term effects on SEU, with coefficients of 0.124 (t-value = 3.183) and 0.492 (t-value = 4.584), respectively, highlighting the rapid responsiveness of technological advancements and economic policies in enhancing sustainable energy utilization across ASEAN nations.

Table 2. ARDL Estimation Results

Run Long Results	*B*	*t-value and sig*	*Summary & Diagnostic Test*	
GIN	0.313	3.648***	R^2	0.678
TIN	0.182	2.462***	Adj. R^2	0.647
EF	0.164	3.584**	D.W.	2.944
EG	0.322	4.952***	X^2SC	3.395 (0.070)
GCF	0.072	1.846	X^2W	5.357 (0.0780)
C	2.765	4.489**	X^2AR	1.583 (0.648)
Short Run Results	*B*	*t-value and sig*	*Summary & Diagnostic Test*	
GIN	0.349	4.583***	R^2	0.705
TIN	0.124	3.183**	Adj. R^2	0.683
EF	0.492	4.584***	X^2SC	3.448 (0.078)
			X^2W	5.597 (0.0713)
			X^2AR	1.194 (0.802)

Note. *GIN = Green Innovation; TIN = Technological Innovation; EF = Economic Freedom; EG = Economic Growth; GCF = Gross Capital Formation; C = Constant term. R² = Coefficient of determination; Adj. R² = Adjusted R²; D.W. = Durbin–Watson statistic; X²SC = Breusch–Godfrey serial correlation test; X²W = White test for heteroskedasticity; X²AR = ARCH test. All variables are significant in the long and short run except GCF. Model diagnostics indicate good model fit and no serial correlation or heteroskedasticity. Significance levels: * = p < 0.10; ** = p < 0.05; *** = p < 0.01.* ***Source(s):*** *Authors' Own Work.*

5 DISCUSSION ON RESULTS

The ARDL results highlight the significant positive relationship between Green Innovation and Sustainable Energy Utilization in ASEAN countries. The coefficient of 0.313 (t-value = 3.648) indicates that an increase in Green Innovation leads to a corresponding increase in Sustainable Energy Utilization over the long run. This finding corroborates with prior studies that emphasize the pivotal role of innovation in advancing sustainable energy practices (Amir et al., 2023; Feng et al., 2024). For instance, Amir et al. (2023) found that countries with higher investments in green technologies exhibit greater adoption rates of renewable energy sources, thereby enhancing sustainable energy utilization. Technological Innovation also shows a positive impact on Sustainable Energy Utilization, although slightly less pronounced with a coefficient of 0.182 (t-value = 2.462) in the long run. This finding aligns with previous research that underscores the importance of technological advancements in driving sustainable energy transitions (Hye et al., 2023; Ofori et al., 2023). They suggested that technological innovations, particularly in energy efficiency and renewable energy technologies, are crucial for achieving sustainable energy goals by reducing reliance on fossil fuels and enhancing energy productivity. Economic Freedom exhibits a significant positive effect on Sustainable Energy Utilization, with a coefficient of 0.164 (t-value = 3.584). This result is consistent with existing literature that links liberal economic policies with improved environmental outcomes, including sustainable energy development (Assi et al., 2020; Ockwell & Byrne, 2016; Zheng et al., 2021). These studies argued that economic freedom fosters innovation and investment in clean technologies, thereby promoting sustainable energy utilization.

Economic Growth shows a robust positive influence on Sustainable Energy Utilization, with a coefficient of 0.322 (t-value = 4.952). This finding is supported by prior studies indicating that economic growth contributes to increased energy demand, necessitating investments in sustainable energy sources to meet growing needs (Costantini & Mazzanti, 2012; Li et al., 2023; Ofori et al., 2023; Rennings, 2000). Li et al. (2023) argued that sustained economic growth provides financial resources and incentives for governments and businesses to prioritize renewable energy projects and infrastructure development. Capital Formation, while not statistically significant in the long run, indicates a nuanced relationship that requires further exploration. Previous studies have suggested mixed findings regarding the impact of capital formation on sustainable energy outcomes (Assi et al., 2020; Costantini & Mazzanti, 2012; Isiksal & Assi, 2022; Li et al., 2023; Ofori et al., 2023; Rennings, 2000). They found that capital investment in renewable energy infrastructure can enhance sustainable energy utilization, whereas Rehman Khan et al. (2023) noted variability across different economic contexts and policy environments.

6 CONCLUSION OF THE STUDY

This study employs the Autoregressive Distributed Lag (ARDL) approach to investigate the determinants of Sustainable Energy Utilization in ASEAN countries, focusing on Green Innovation, Technological Innovation, Economic Freedom, Economic Growth, and Capital Formation. Using data from 1995 to 2023, sourced from reputable international databases, the study provides insights into the factors shaping sustainable energy transitions in the region. The findings underscore the significant roles of Green Innovation, Technological Innovation, Economic Freedom, and Economic Growth in promoting Sustainable Energy Utilization across ASEAN countries. Green Innovation emerges as a pivotal driver with both long-term and short-term impacts on sustainable energy adoption. Technological Innovation, Economic Freedom, and Economic Growth also play crucial roles, highlighting the importance of fostering innovation and maintaining conducive economic environments to support sustainable energy transitions. However, the impact of Capital Formation shows variability and requires further investigation due to its insignificant relationship with sustainable energy outcomes.

6.1 Research Implications

This study contributes theoretically by empirically demonstrating the drivers of Sustainable Energy Utilization in ASEAN countries. It expands the understanding of how innovation, economic policies, and economic development interact to influence sustainable energy outcomes, providing a nuanced perspective on sustainable development theories. The findings suggest that sustainable energy transitions are not only driven by technological advancements but also by institutional and economic factors, emphasizing the interdisciplinary nature of sustainable development. Practically, the findings suggest actionable insights for policymakers in ASEAN countries to accelerate the transition towards sustainable energy systems. Policymakers should prioritize investments in green and technological innovations, enhance economic freedom to attract sustainable energy investments, and foster economic growth to support energy demand growth sustainably. These actions are crucial for achieving energy security, reducing environmental impacts, and enhancing economic resilience in the face of global energy challenges. From a policy perspective, this research emphasizes the importance of implementing supportive policy frameworks that incentivize green technologies and sustainable practices. Policies should aim to create a conducive environment for innovation, facilitate technology transfer, and promote collaboration among ASEAN countries to leverage collective strengths in achieving regional energy goals. Policymakers can use these findings to design policies that balance economic growth with environmental sustainability, ensuring long-term prosperity and resilience.

6.2 Study Limitations and Future Research Directions

Despite its contributions, this study has several limitations. Firstly, the use of aggregate data may overlook intra-regional variations within ASEAN countries, warranting future studies at national or sub-national levels to capture localized impacts. Secondly, the study's focus on selected variables may omit other potentially influential factors impacting Sustainable Energy Utilization, such as cultural factors and geopolitical dynamics. Lastly, while robust, the ARDL approach assumes linear relationships and stationary data, which may not fully capture dynamic and non-linear interactions in sustainable energy transitions. Future research could address these limitations by incorporating finer-grained data and exploring additional variables such as policy effectiveness, social acceptance of renewable energy technologies, and the role of international cooperation in promoting sustainable energy transitions. Longitudinal studies could track the evolution of sustainable energy policies and their impacts over time, offering insights into the effectiveness of different policy interventions under varying economic and environmental conditions. Comparative studies across different regions or countries could also provide insights into the generalizability of findings and inform global efforts towards achieving sustainable development goals.

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