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Exploring Smart Renewable Investment in Green Financial Mechanism for Achieving Carbon Neutrality: An Empirical Analysis of the ASEAN Economy

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Abstract

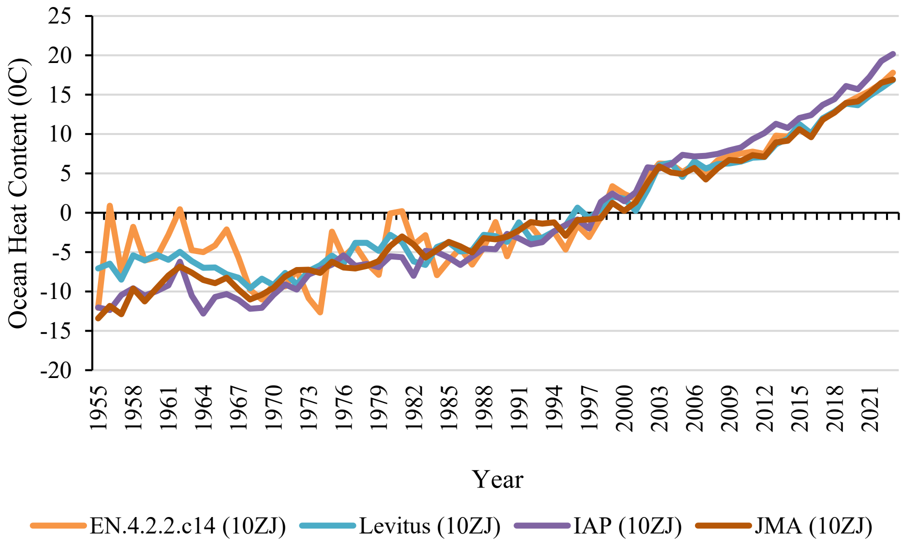
Smart renewable energy investment is increasingly recognized as a critical component of green financial mechanisms aimed at achieving carbon neutrality, particularly within the ASEAN region, which faces the dual challenge of sustaining economic growth while mitigating environmental degradation. However, the effectiveness of such investments is influenced by complex factors, including geopolitical instability, environmental constraints, and disparities in financial access. Our study empirically examines the dynamic relationship between smart renewable investment, green finance, and carbon emissions in seven ASEAN economies over the period 2001–2023. Employing second-generation panel cointegration techniques, specifically the Continuously Updated Fully Modified and Continuously Updated Bias-Corrected estimators, this analysis accounts for cross-sectional dependence, heterogeneity, and non-stationarity in the panel data. The results reveal that both renewable energy investment and green finance exert a statistically significant negative impact on CO_2 emissions, confirming their effectiveness in facilitating the region's transition toward low-carbon development. In contrast, economic indicators such as foreign direct investment, gross domestic product growth, and gross fixed capital formation are positively correlated with emissions, highlighting the environmental costs associated with traditional growth trajectories. Moreover, geopolitical risk is identified as a critical factor exacerbating emissions, suggesting that regional instability can hinder sustainable energy deployment and delay decarbonization efforts. The policy implications of these findings highlight the importance of establishing stable and harmonized green finance frameworks in ASEAN, including fiscal incentives, public–private collaboration, and the integration of geopolitical risk assessments into national energy planning. Furthermore, the development of regional green capital markets and innovative mechanisms such as emissions trading and carbon pricing is deemed crucial to strengthening cross-border investment flows and supporting the transition toward sustainable development.

Keywords:
ASEAN economy, carbon neutrality, geopolitical risk, green financial mechanism, smart renewable investment

1. Introduction

In response to growing environmental concerns, researchers, especially those in the field of economics, have increasingly directed their attention to the intersection of economic issues and environmental factors (Kumar & Radulescu, 2024). To effectively address the diverse environmental challenges and attain carbon neutrality in ASEAN countries, it is pivotal to conduct a thorough deep dive into relevant policies, underpinned by comprehensive research and studies. Addressing environmental degradation and pursuing carbon neutrality is a global imperative, as demonstrated by international agreements such as the Paris Agreement (Huang et al., 2024). The Paris Agreement, which was adopted by 195 countries at the end of the 21st Conference of the Parties in Paris in late 2015, reinvigorated global dedication to collaborative climate change policies and initiatives, while also paving the way for new approaches in international climate policy discussions (Seo, 2017; UNFCCC, 2015). Human activities, particularly unsustainable development practices such as resource exploitation that generate waste and pollution harmful to ecosystems, have evidently contributed to the rise in greenhouse gas (GHG) concentrations (Boylan et al., 2018). In 2019, the global average concentrations of GHG, CO2, CH4, and N2O had increased by 47%, 156%, and 23%, respectively, relative to pre-industrial levels in 1750 (IPCC, 2021). Concurrently, the ASEAN Centre for Energy (ACE) projects that GHG emissions in the ASEAN region will rise by 147% between 2017 and 2040 (ACE, 2017). Further, researchers and scientists, including Helge F. Goessling and his team at the Alfred Wegener Institute in Bremerhaven, by analyzing satellite data and weather records, have shown that over the course of this century, Earth has been progressively reflecting a smaller amount of sunlight into space.

According to the Climate Dashboard published by the Met Office, 90% of the excess energy trapped in the Earth's system due to anthropogenic greenhouse gas emissions is absorbed by the oceans. Ocean heat content is a direct measure of the accumulation of this energy. Changes in ocean temperature can affect how much oxygen and carbon dioxide can dissolve in seawater, which in turn can alter the amounts of these gases in the atmosphere. Overall, ocean heat content has increased since 1955 (Figure 1). This increase is generally more stable compared to surface temperature but remains linked to the energy levels present in the Earth system. Therefore, it can be concluded that there has been a significant increase in carbon dioxide emissions on Earth, along with greenhouse gas emissions, both of which have contributed to rising temperatures in the oceans and on the surface.



Source: Met Office Climate Dashboard (Data has been processed)
Figure 1. Ocean heat content.

This continuous warming trend has intensified global concerns, making climate change an increasingly alarming issue in recent years. In fact, over the past decade, approximately 25% of anthropogenic CO_2 emissions, those generated by human activities, have been absorbed by the oceans, highlighting the critical role of marine ecosystems in regulating the Earth's climate. Upon absorption, CO2 reacts with seawater, leading to a reduction in pH levels through a process commonly known as acidification, which poses significant risks to marine ecosystems. An additional 25% of carbon emissions are sequestered by terrestrial plants, initially stored in living tissues and subsequently in dead organic matter within the soil. Consequently, roughly half of the greenhouse gas emissions responsible for Earth's warming are accounted for (Met Office Climate Dashboard, 2024). This underscores the importance of smart renewable investment in reducing emissions and supporting the process of sustainable development in Indonesia through the strengthening and promotion of innovative and sustainable green financing sources, which are grounded in the interconnection between financial development and economic growth. Accordingly, the issuance of green bonds, the provision of green loans, and investments in green projects by financial institutions serve as incentives for businesses to adopt environmentally friendly practices in their economic activities.

Numerous studies have consistently highlighted the importance of expanding renewable energy to meet carbon reduction goals, yet this expansion is hindered by substantial obstacles, such as inadequate financial resources and poor allocation of available resources. In this context, green finance has become an essential tool, gaining widespread recognition for its ability to address climate change and promote environmental sustainability. Guo et al. (2023) highlight that green finance has evolved into an indispensable mechanism for promoting renewable energy development and plays a pivotal role in advancing carbon neutrality agendas across various nations. Complementing this view, Cheng et al. (2023) demonstrate that the advancement of green finance generates substantial hedging effects aligned with carbon emission reduction objectives, thereby serving as an effective mechanism for incentivizing carbon neutrality policies. Additionally, Shaikh et al. (2024) show that policy measures backed by green investments play a crucial role in enhancing environmental sustainability over both short and long periods. These findings emphasize the need for sustainable economic growth. To achieve this, it is essential to create innovative green financing strategies that are firmly rooted in the connection between financial progress and economic expansion.

The success of green finance initiatives is closely intertwined with current geopolitical circumstances, as conflicts in global politics significantly affect the energy sector, causing fluctuations in energy prices and rising inflation. This instability undermines the financial viability and strategic investments needed for renewable energy projects, making it a crucial factor in reaching carbon neutrality. These factors influence both the direction of investments and pricing models within the green energy industry, while an over-dependence on fossil fuels worsens environmental harm and intensifies geopolitical disputes worldwide. Furthermore, the study by Luo & Sun (2024) demonstrates that geopolitical risks are found to exacerbate carbon-dependent consumption patterns. In a similar vein, Khouri (2019) emphasises that conflicts in regions such as the Arab states and the United States have negatively impacted environmental sustainability by damaging natural ecosystems and increasing CO2 emissions. As a result, shifting to renewable energy sources is recommended as a viable approach to reduce a nation's geopolitical risks tied to reliance on unstable energy providers (Dong et al., 2023a). Additionally, the growing geopolitical risks present a significant obstacle to foreign direct investment, which is crucial for driving both economic and environmental sustainability (Du et al., 2023). Moreover, implementing green finance policies to facilitate the energy transition is vital for mitigating geopolitical tensions and addressing the challenges posed by global warming and carbon-heavy practices (Sweidan, 2021).

This research aims to assess and enhance efforts toward carbon neutrality in ASEAN nations, focusing on tailoring strategies to the unique resources and infrastructure of each country. It examines the significant relationship between renewable energy investment (REI) and green innovation, considering the challenges posed by geopolitical risks that influence the region's economic landscape. By combining these elements into an integrated analytical model, our study addresses gaps in the concurrent analysis of these factors, along with other variables. Previous studies, such as that by Liu (2023), Zhang et al. (2021), and Zhang (2022), have emphasized the positive impact of green innovation on managing renewable resource use in the manufacturing and agricultural sectors. However, the progress of renewable energy initiatives aimed at carbon neutrality faces considerable challenges, largely due to limited financial resources and inefficient capital allocation (Guo et al., 2023).

Our study places particular emphasis on smart green investment as a critical economic activity for addressing climate change, identifying it as a fundamental driver of green investment development and carbon neutrality strategies in ASEAN. Furthermore, we seek to bridge a gap in the existing literature concerning the effects of geopolitical risks on environmental performance by proposing that smart green investment can substantially foster carbon neutrality, especially within ASEAN economies. In addition, the research utilizes advanced estimation techniques, including Continuously Updated Fully Modified (CUP-FM), Continuously Updated Bias-Corrected (CUP-BC), Common Correlated Effects Mean Group (CCEMG), and Augmented Mean Group (AMG), to analyze the relationships between different indicators and greenhouse gas emissions in ASEAN countries. This approach is deemed suitable for addressing challenges such as cross-sectional dependence, omitted variable bias, reverse causality, and autocorrelation, thereby providing more reliable and policy-relevant insights. The structure of the study is as follows: Section 2 offers a detailed explanation of the methods and materials used in the analysis. Section 3 presents the results of the study along with an extensive discussion, while Section 4 concludes the research and outlines the associated policy recommendations.

2. Methods and Materials

2.1. Data and Variables

This study utilizes a comprehensive panel dataset encompassing seven ASEAN member states (i.e., Brunei Darussalam, Indonesia, Malaysia, Myanmar, the Philippines, Singapore, and Thailand) from 2001 to 2023. The inclusion of these countries is guided by the availability, consistency, and completeness of data across key variables, including environmental efficiency, renewable energy investment, green finance, geopolitical risk, and macroeconomic performance. Cambodia, Laos, and Vietnam were excluded from the analysis due to substantial data deficiencies that compromise the reliability of empirical estimations. The dependent variable in this study is carbon dioxide (CO_2) emissions, measured through the lens of production-based CO_2 productivity. This metric captures the efficiency with which economic output is generated per unit of CO_2 emissions, serving as a critical proxy for evaluating the environmental sustainability of production systems. It reflects the ability of an economy to decouple carbon emissions from output growth, thereby offering an empirical basis for assessing environmental performance in the context of economic development. The study adopts the methodological framework of Kirikkaleli & Addai (2023), wherein CO_2 emissions measured in kilograms are used to assess progress toward carbon neutrality. Data for CO_2 emissions are sourced from the Organisation for Economic Co-operation and Development (OECD) database, ensuring high standards of international comparability and data integrity. The overarching objective is to investigate the extent to which ASEAN countries can mitigate environmental degradation while sustaining or enhancing economic productivity.

The main independent variables are renewable energy investment (REI) and green finance investment (GFI). Renewable energy investment encompasses national investments in bioenergy, hydroelectricity, solar, and wind power, evaluated relative to overall energy investments. These investments reflect a country's commitment to transitioning toward cleaner energy systems and reducing fossil fuel dependence. Companies in this sector are challenged to optimize operational strategies, including pricing, production capacity, and profitability, while balancing environmental and societal responsibilities, as emphasized by Lu et al. (2022) and Peng et al. (2022). Data on renewable energy investment are sourced from IRENA (2023) providing detailed country-level insights into renewable energy trends.

Green finance investment denotes a set of financial strategies aimed at promoting resource conservation, enhancing environmental sustainability, and supporting climate change mitigation efforts. As outlined by Udeagha & Ngepah (2023), green finance comprises various instruments such as green credits, green investments, and green securities. These tools are instrumental in advancing national environmental objectives by channeling financial resources toward low-carbon technologies, renewable energy development, and climate-resilient infrastructure. Through such targeted allocations, green finance contributes significantly to ecological preservation and the transition to sustainable economic systems. Collectively, they contribute to sustaining long-term ecological integrity while fostering a transition toward environmentally responsible economic systems. The data, sourced from the Food and Agriculture Organization (FAO) and the World Development Indicators (WDI), capture consolidated central government expenditure (excluding social security funds) and general government final consumption expenditure as a share of gross domestic product (GDP), aligning with established measurement frameworks described by Dong et al. (2023) and Zhang (2022).

To enrich the analysis, the study integrates geopolitical risk (GPR) as an additional explanatory variable. The GPR Index, developed by Caldara and Iacoviello (2022), measures the frequency of geopolitical disturbances, nuclear threats, war risks, and terrorism reported across eleven major international newspapers, providing a credible proxy for external political and security uncertainties. This index is crucial for examining how international instability may hinder renewable energy expansion and sustainable finance efforts, as highlighted by Hassan et al. (2023), Nonejad (2022) and Zhao et al. (2023). The GPR dataset spans the entire study period, covering January 2001 to December 2023.

To ensure the robustness of the empirical model, key indicators of economic performance are incorporated as control variables, namely foreign direct investment (FDI), GDP growth, and gross fixed capital formation (GFCF). FDI is operationalized as net inflows expressed as a percentage of GDP, GDP growth is measured in terms of per capita GDP at constant 2015 USD, and GFCF reflects capital investments in physical infrastructure and productive assets. These variables, sourced from the WDI database, are included to account for macroeconomic dynamics that may influence the relationship between green investments and carbon emissions. Their inclusion is consistent with the analytical frameworks proposed by Ali et al. (2023) and Zhang (2022), who emphasize the importance of controlling for economic growth trajectories and capital formation when evaluating environmental sustainability outcomes. By integrating environmental, financial, geopolitical, and economic dimensions, this study aims to provide a comprehensive understanding of the pathways to carbon neutrality in ASEAN economies. A summary of the variables, including definitions, roles, and data sources, is presented in Table 1.

Table 1. Explanation of the variables.

Variables	Definition and Measure	Source
Dependent Variable		
Environmental Efficiency (CO_2)	Energy-related CO_2 emissions expressed in U.S. dollars per kilogram, derived from production-based CO_2 productivity in relation to GDP, serving as a proxy for environmental efficiency.	OECD
Independent Variable		
Renewable Energy Investment (REI)	Investments allocated to electricity generation from bioenergy, hydropower, solar, and wind sources, representing financial commitments toward renewable energy development	IRENA (2023)
Green Finance Investment (GFI)	Consolidated central government expenditure, excluding allocations to social security funds — measured in constant 2015 USD, combined with general government final consumption expenditure as a percentage of GDP	FAO; WDI
Geopolitical Risk (GPR)	Geopolitical risk index	Iacoviello, Matteo (https://www.matteoiacoviello.com/gpr.htm)
Control / Mediating Variable: Economic Performance		
Foreign direct investment (FDI)	FDI is measured as net inflows relative to GDP (%).	WDI
Gross Domestic Product (GDP)	GDP per capita in constant 2015 USD.	WDI
Gross Fixed Capital Formation (GFCF)	GFCF in current U.S. dollars	WDI

2.2. Modeling Equations/Model Specification

Grounded in the theoretical foundations and empirical insights from the existing literature, our study formulates a baseline functional model to examine the dynamic interplay among key macroeconomic, financial, and environmental variables within a panel data framework. The model is designed to assess the impact of REI, GFI, FDI, GDP growth, GFCF, and GPR on CO_2 emissions, which are employed here as a proxy for environmental efficiency. The inclusion of independent variables is theoretically justified. REI reduces CO_2 by shifting the energy mix (Lu et al., 2022). GFI channels capital into climate-resilient projects (Guo et al., 2023). GDP, FDI, and GFCF often increase emissions via industrial growth (Chen et al., 2024). GPR delays renewable deployment and strengthens fossil fuel dependency (Hassan et al., 2023). The functional specification of the model is expressed in Equation 1.

$$CO_2 = f(REI, GFI, FDI, GDP, GFCF, GPR) \tag{1}$$

To improve data consistency and mitigate potential issues related to heteroscedasticity, all variables in the model are expressed in their natural logarithmic forms. Logarithmic transformation not only stabilizes variance but also enhances the interpretability of elasticities and improves the overall model fit. This approach contributes to more reliable and robust parameter estimates compared to linear specifications. Accordingly, the logarithmically transformed econometric model is represented in Equation 2.

$$lnCO_2 = \beta_0 + \beta_1 \ln REI_{it} + \beta_2 \ln GFI_{it} + \beta_3 \ln FDI_{it} + \beta_4 \ln GDP_{it} + \beta_5 \ln GFCF_{it} + \beta_6 \ln GPR_{it} + \varepsilon_{it} \tag{2}$$

In this model, β_0 denotes the intercept or constant term. The subscript i refers to each cross-sectional unit, representing the seven ASEAN countries included in the analysis ($i = 1, \dots ,7$), while t corresponds to the time dimension, spanning the period from 2001 to 2023. The slope coefficients β_1 through β_6 represent the estimated elasticities associated with the natural logarithmic values of REI, GFI, FDI, GDP, GFCF, and GPR, respectively. The term ε_{it}captures the stochastic disturbance or idiosyncratic error component of the model.

2.3. Estimation Strategy/Econometrics Estimation Approach

This study applies advanced panel econometric methodologies tailored to address key methodological issues, namely endogeneity, cross-sectional dependence, and slope heterogeneity. Specifically, second-generation panel cointegration methods are employed, including the CUP-FM estimator and the CUP-BC estimator, developed by Bai et al. (2009), which are particularly suitable for large-N, large-T panels and capable of correcting for both cross-sectional dependence and non-stationarity to ensure robust and consistent long-run estimates. To further validate the robustness of the results, the analysis also incorporates the CCEMG and the AMG estimators, both of which account for unobserved common factors and heterogeneity across cross-sections. Together, these approaches enhance the reliability of the empirical findings and provide a comprehensive framework for examining long-run relationships in the ASEAN context.

2.3.1. Cross-Sectional Dependence

Prior to estimation, it is essential to examine cross-sectional dependence to ensure reliable panel data analysis. Ignoring cross-sectional dependence can result in biased and inefficient estimates, especially in macro-panel settings. This study employs two established approaches: the Lagrange Multiplier (LM) test proposed by Breusch & Pagan (1980) and the cross-sectional dependence test developed by Pesaran (2004). The LM test is formulated in Equation 3.

$$CD = T \sum_{i=1}^{N-1} \sum\nolimits_{j=i+1}^{N} \hat{p}_{ij}^2 \tag{3}$$

where T denotes the number of periods, N is the cross-sectional dimension, and $\hat{p}_{ij}$ represents the correlation coefficient between cross-sectional units i and j. Complementarily, the Pesaran (2004) cross-sectional dependence test is expressed in Equation 4.

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum\nolimits_{j=i+1}^{N} p_{ij} \tag{4}$$

The null hypothesis (H_0) states cross-sectional independence, while the alternative hypothesis (H_1) suggests cross-sectional dependence among units. Detecting cross-sectional dependence is a critical diagnostic step, as the presence of cross-sectional correlation directly influences the choice of appropriate second-generation panel estimators.

2.3.2. Unit Root Tests

To determine the integration properties of the variables, unit root testing is conducted following the cross-sectional dependence assessment. Given that first-generation unit root tests, such as Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS), are limited under cross-sectional dependence (Lv and Xu, 2018), this study applies second-generation methods, namely the Cross-Sectionally Augmented IPS (CIPS) and Cross-Sectionally Augmented Dickey–Fuller (CADF) tests developed by Pesaran (2007). The CADF regression equation is specified in Equation 5. CA_{t-1} and ΔCA_{t-1} are the cross-sectional averages, and μ_{it} is the error term.

$$\Delta CA_{i,t} = \phi_i + \phi_i Z_{i,t-1} + \phi_i CA_{t-1} + \sum_{l=0}^{p} \phi_{il} \Delta CA_{t-1} + \sum_{l=0}^{p} \phi_{il} \Delta CA_{i,t-1} + \mu_{it} \tag{5}$$

The CIPS test statistic is calculated using Equation 6. $CADF_i$ denotes the individual cross-section CADF statistic. The null hypothesis (H_0) indicates the presence of a unit root (non-stationarity), while the alternative hypothesis (H_1) suggests stationarity. Employing these second-generation tests ensures robust inferences by accounting for potential cross-sectional correlations in the panel dataset.

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF_i \tag{6}$$

2.3.3. Panel Cointegration Test

Prior to estimating the long-run parameters, the existence of cointegration among the variables is assessed. Conventional first- and second-generation panel cointegration tests, such as those proposed by Larsson et al. (2001), McCoskey and Kao (1998), Pedroni (2004), and Westerlund (2005, 2007) exhibit notable limitations, particularly in their inability to simultaneously account for structural breaks and cross-sectional dependence, both of which are critical considerations in macro-panel data analysis. As highlighted by Phillips & Sul (2003), applying conventional cointegration techniques under such conditions may produce misleading or unreliable results.

To overcome these limitations, our study employs the Westerlund & Edgerton (2008) panel cointegration test, which explicitly accounts for cross-sectional dependence, autocorrelation, and structural breaks. The test statistics are defined in Equation 7. $\hat{\phi}_i$ is the least squares estimator, $\hat{\sigma}_i$ is its standard error, and $SE(\hat{\phi}_i)$ denotes the standard error of $\hat{\phi}_i$. The null hypothesis (H_0) assumes no cointegration (i.e., no long-run equilibrium relationships among the variables), while the alternative hypothesis (H_1) suggests the existence of cointegration, indicating stable long-term relationships.

$$LM_{\tau} = \frac{\hat{\phi}_i}{SE(\hat{\phi}_i)}, \quad LM_{\phi} = T\frac{\widehat{\omega}_i}{\hat{\sigma}_i} \tag{7}$$

2.3.4. Long-Run Analysis

Various econometric approaches, such as pooled OLS, GMM, and standard OLS, have been employed in prior studies to estimate the effects of independent variables on dependent outcomes. While these methods have certain advantages, they are limited in addressing key challenges such as cross-sectional dependence. To overcome these limitations, our study applies the CUP-FM estimator proposed by Bai and Kao (2006) and the CUP-BC estimator developed by Bai et al. (2009), following recent applications in Ahmed et al. (2020), Ulucak and Bilgili (2018), and Zafar et al. (2019). Given the large sample size and strong statistical power of the dataset, CUP-FM and CUP-BC are appropriate and robust estimation techniques. These methods effectively handle issues of cross-sectional dependence, endogeneity, and autocorrelation, producing unbiased and reliable long-run parameter estimates, even when regressors are exogenous or when mixed integration orders (I(0)/I(1)) are present.

Specifically, the CUP-FM estimator maintains a consistent and limited distribution of model parameters, continuously updating estimates through simulations until convergence. The factor model underlying the CUP estimators is formalized in Equation 8. $(\hat{\beta}_{Cup}, \hat{F}_{Cup})$ refers to the solution of the two nonlinear Equations 9 and 10.

$$(\hat{\beta}_{Cup}, \hat{F}_{Cup}) = \operatorname{argmin} \frac{1}{nT^2} \sum_{i=1}^{n} (y_i - x_i\beta)' M_F (y_i - x_i\beta) \tag{8}$$

$$\hat{\beta} = \left(\sum_{i=1}^{n} \acute{x}_i M_{\hat{F}} x_i \right)^{-1} \sum_{i=1}^{n} \acute{x}_i M_{\hat{F}} y_i \tag{9}$$

$$\widehat{FV}_{nT} = \left[\frac{1}{nT^2} \sum_{i=1}^{n} (y_i - x_i\hat{\beta})(y_i - x_i\hat{\beta}) \right]' \hat{F} \tag{10}$$

In their foundational contribution, Bai et al. (2009) introduced CUP-FM and CUP-BC estimators, which have since become instrumental in panel data econometrics involving exogenous regressors. These estimators are especially well-suited for panel datasets exhibiting mixed integration orders such as I(0) and I(1) and are robust in yielding consistent long-run parameter estimates, even when endogeneity is present. Their formulation is grounded in the transformation matrix $M_F = I_T - T^{-2}FF'$, where $\hat{F}'\hat{F}/T^2 = I_r$, and V_{nT} represents a diagonal matrix comprising the rrr most dominant eigenvalues.

The CUP-FM and CUP-BC estimators are particularly advantageous in empirical settings requiring high precision, especially when the time dimension is limited. Their ability to accommodate structural complexities, including cross-sectional dependence and endogenous regressors, makes them highly effective for applied macro panel analysis. As such, their application enhances the credibility and robustness of econometric inference and maximizes the benefits of second-generation panel cointegration techniques.

Despite their strengths in estimating average and long-run effects, CUP-FM and CUP-BC have limitations in capturing the dynamic heterogeneity underlying multifaceted processes such as carbon neutrality, renewable energy investment, green finance, and geopolitical risk. To address these limitations and strengthen the empirical analysis, this study further employs the AMG estimator, which serves as a complementary robustness check to validate and enrich the core findings derived from the CUP-based estimations. The inclusion of the AMG method provides an additional layer of validation for the empirical results. As highlighted by Sadiq et al. (2023), one of the principal advantages of the

AMG approach lies in its ability to accommodate the heterogeneity in the energy–carbon emissions nexus. This methodological robustness enhances the reliability of the results by mitigating the influence of heteroskedasticity and reducing the potential distortion caused by outliers.

2.3.4. Granger Causality Test

While the CUP-FM and CUP-BC estimations provide robust long-run relationships, they do not reveal the directionality of causality among variables, which is a crucial element for formulating policy recommendations. To address this, our study employs the Dumitrescu and Hurlin (2012) panel Granger causality test to examine the causal dynamics between the key variables. This method generates two main statistics: the $\overline{\boldsymbol{W}}$ statistic, which reflects the average of individual Wald statistics across cross-sections, and the $\overline{\boldsymbol{Z}}$ statistic, which follows a standard normal distribution and enables inference in heterogeneous panel settings. The general model is specified in Equation 11. The p is the lag length, β_i^j represents the autoregressive coefficients, and γ_i^j captures the impact of lagged explanatory variables $T_{i,t-j}$ on the dependent variable $Z_{i,t}$.

$$z_{i,t} = \alpha_i + \sum_{j=1}^{p} \beta_i^j Z_{i,t-j} + \sum_{j=1}^{p} \gamma_i^j T_{i,t-j} \tag{11}$$

3. Results and Discussions

3.1. Estimation Results

Table 2 presents the descriptive statistics for the variables employed in this study across the ASEAN economies from 2001 to 2023. The logarithmic transformation applied to all variables ensures comparability and reduces heteroscedasticity in the dataset. The average value of CO_2 emissions (LCO_2) is 4.25, with a minimum of 3.10 and a maximum of 5.50, indicating considerable variation in environmental efficiency across countries. Renewable energy investment (LREI) records a mean of 2.15, suggesting that while ASEAN economies are increasingly directing capital toward renewable sources, significant disparities remain, as reflected in the wide range between 1.05 and 3.50. Green finance investment (LGFI), with a mean of 1.85 and relatively lower variability (standard deviation of 0.40), demonstrates the growing but still modest role of green financial instruments in the region. Foreign direct investment (LFDI) has a mean of 2.75, ranging from 1.60 to 4.20, underscoring the heterogeneity of FDI inflows across ASEAN and their potential influence on energy transition trajectories. GDP per capita (LGDP) exhibits a mean of 8.95, spanning from 7.10 to 11.00, reflecting the structural differences between high-income economies such as Singapore and lower-income economies like Myanmar or the Philippines. Similarly, gross fixed capital formation (LGFCF) shows a mean of 9.10, with a wide range (7.50 to 10.80), highlighting variations in domestic investment capacity. The geopolitical risk index (LGPR) displays relatively low dispersion, with values ranging from 1.00 to 2.20. Although the variation is narrower compared to economic variables, the index remains critical, as geopolitical uncertainties have the potential to disrupt investment flows and delay the deployment of renewable energy projects. The descriptive statistics confirm significant heterogeneity across ASEAN countries in terms of economic performance, renewable investment, and exposure to geopolitical risks. These disparities justify the use of advanced panel econometric methods to capture cross-sectional dependence and heterogeneity in the subsequent analysis.

Table 3 displays the correlation matrix, revealing a positive relationship between CO_2 emissions and several macroeconomic variables, including foreign direct investment, economic growth, gross fixed capital formation, and geopolitical risk. These results suggest that economic expansion and the intensification of capital flows within the ASEAN region may exacerbate environmental pressures. Conversely, the findings demonstrate a negative correlation between CO_2 emissions and both renewable energy investment and green finance, highlighting the potential of clean energy initiatives and sustainable financial instruments to alleviate environmental degradation. Some correlations may appear counterintuitive. For example, GDP and REI are negatively correlated. This can be explained by the fact that highly developed economies such as Singapore tend to invest in renewable projects abroad rather than domestically, which reduces domestic REI in the dataset. Similarly, the negative correlation between FDI and REI reflects that foreign investors in ASEAN often prioritize non-renewable sectors such as mining and manufacturing instead of clean energy. These interpretations are consistent with prior findings by Zhang (2022). The empirical analysis commences with tests for cross-sectional dependence, followed by second-generation panel unit root diagnostics and cointegration procedures. These steps are implemented to ensure the robustness of the dataset and to verify the existence of long-term equilibrium relationships among the variables.

Table 2. Descriptive statistics.

Variables	Mean	Std. Dev.	Min	Max
LCO_2	4.25	0.65	3.1	5.5
LREI	2.15	0.55	1.05	3.5
LGFI	1.85	0.4	1.0	2.6
LFDI	2.75	0.6	1.6	4.2
LGDP	8.95	1.05	7.1	11.0
LGFCF	9.1	0.95	7.5	10.8
LGPR	1.55	0.35	1.0	2.2

Table 3. Correlation test results.

Variables	LCO_2	LREI	LGFI	LFDI	LGDP	LGFCF	LGPR
LCO_2	1.000	−0.512	−0.438	0.542	0.615	0.589	0.461
LREI	−0.512	1.000	0.421	−0.310	−0.275	−0.225	−0.195
LGFI	−0.438	0.421	1.000	−0.260	−0.305	−0.240	−0.180
LFDI	0.542	−0.310	−0.260	1.000	0.575	0.530	0.450
LGDP	0.615	−0.275	−0.305	0.575	1.000	0.680	0.490
LGFCF	0.589	−0.225	−0.240	0.530	0.680	1.000	0.510
LGPR	0.461	−0.195	−0.180	0.450	0.490	0.510	1.000

Table 4 presents the results of the cross-sectional dependence tests, utilizing the Breusch–Pagan LM, Pesaran scaled LM, and Pesaran cross-sectional dependence statistics. The findings consistently reject the null hypothesis of cross-sectional independence at the 1%, 5%, and 10% significance levels across all variables, thereby confirming the existence of statistically significant cross-sectional dependence among the panel units. This evidence suggests a considerable degree of economic and environmental interdependence among the ASEAN economies included in the sample. Within such an integrated regional framework, exogenous shocks, such as an abrupt increase in foreign direct investment or heightened geopolitical risk in one country, are likely to transmit across national borders and produce spillover effects throughout the region. In addition, the assumption of cross-sectional independence is empirically unsupported in this context. Failure to account for such dependence may result in biased or inconsistent parameter estimates, as highlighted by Pesaran (2004). Considering these findings, the next phase of the empirical analysis entails examining the integration properties of the variables through the application of second-generation panel unit root tests, which are specifically designed to address cross-sectional dependence.

This study further examines the stationarity properties of the variables by employing the CIPS and CADF unit root tests, as presented in Table 5. These tests are utilized to determine the integration order of each variable while explicitly accounting for cross-sectional dependence. The results indicate a heterogeneous integration pattern across the panel. At their levels, most variables fail to reject the null hypothesis of a unit root, suggesting non-stationarity. However, following first differencing, all variables become stationary at the 1% significance level under both the CIPS and CADF methodologies. These findings confirm that the variables are integrated of order one, I(1), thus satisfying the prerequisite for employing panel cointegration techniques in the subsequent stages of the empirical analysis.

Table 4. Cross-sectional dependence tests results.

Variables	Breusch–Pagan LM	Prob	Pesaran scaled LM	Prob	Pesaran CD	Prob
LCO_2	65.274***	0.000	25.614**	0.028	5.234***	0.000
LREI	12.487***	0.000	62.918***	0.010	3.987***	0.001
LGFI	48.372***	0.000	18.415**	0.042	6.014***	0.000
LFDI	33.129***	0.000	29.765**	0.035	5.873***	0.000
LGDP	40.658***	0.000	21.143**	0.047	4.256***	0.002
LGFCF	98.452***	0.000	13.629*	0.053	3.789***	0.004
LGPR	25.738***	0.000	45.301***	0.012	4.967***	0.001

* , ** , *** represent significance at 10%, 5%, and 1% levels, respectively.

Table 5. Results of the CIPS and CADF unit root tests.

Variables	CIPS Level	CIPS Difference	CADF Level	CADF Difference
LCO_2	−0.512	−2.845***	−2.954	−4.112***
LREI	−1.205**	−4.210***	−3.456	−5.301***
LGFI	−1.678	−3.755***	−3.001***	−6.101***
LFDI	−2.315	−4.085***	−4.512***	−4.876***
LGDP	−1.812**	−6.421***	−1.765	−4.009***
LGFCF	−0.621	−5.310***	−1.321**	−1.512***
LGPR	−1.625	−4.452***	−1.912***	−1.154***

Note: H_0 is unit root; The 10%, 5%, and 1% levels are indicated by *, **, and ***, corresponding to $P < 0.1$, 0.05, 0.01, respectively.

Table 6 presents the results of the Westerlund & Edgerton (2008) panel cointegration test across three structural specifications: no shift, mean shift, and regime shift. The test statistics for both the $LM\tau$ and $LM\phi$ models are statistically significant at the 1% level across all specifications, providing strong evidence of long-run cointegration among the variables. These findings confirm the existence of a stable long-term equilibrium relationship among renewable energy investment, green finance, foreign direct investment, economic growth, gross fixed capital formation, geopolitical risk, and CO_2 emissions within the ASEAN context. The consistency of the results across different structural break scenarios further supports the appropriateness of applying long-run estimation techniques in the subsequent stages of the empirical analysis.

Table 6. Findings from the Westerlund and Edgerton cointegration test.

Model	No shift		Mean shift		Regime shift	
	Statistic	p-value	Statistic	p-value	Statistic	p-value
$LM\tau$	−3.102	0.002	−4.978	0.000	−3.451	0.000
$LM\phi$	−4.912	0.000	−4.205	0.000	−5.123	0.000

Note: Models are run with a maximum of five factors.

Upon confirming the existence of a long-run equilibrium relationship through the panel cointegration analysis, the study advances to the estimation of long-term elasticities utilizing the CUP-FM and CUP-BC methods, as presented in Table 7. All coefficient estimates are statistically significant at the 1% level ($p < 0.01$), thereby demonstrating the robustness of the results.

The findings reveal a significant negative association between CO_2 emissions and both renewable energy investment (REI) and green finance (GFI) across ASEAN countries. Specifically, a 1% increase in REI corresponds to reductions in CO_2 emissions by 5.92% and 3.77%, as estimated by the CUP-FM and CUP-BC methods, respectively. Similarly, a 1% increase in GFI is associated with decreases of 1.53% (CUP-FM) and 0.22% (CUP-BC) in CO_2 emissions. These results underscore the essential role of renewable energy initiatives and sustainable financial mechanisms in facilitating the region's transition toward carbon neutrality. The observed trends confirm that investments in REI and GFI are not only consistent with environmental objectives but also make a substantial contribution to emissions reduction.

Table 7. Results of the CUP-FM and CUP-BC estimations.

Variables	CUP-FM Coefficient	t-stat	CUP-BC Coefficient	t-stat
LREI	−5.923***	−22.145	−3.765***	−35.240
LGFI	−1.532***	−18.567	−0.215***	−23.450
LFDI	0.1981***	2.987	0.3412***	8.945
LGDP	0.0153***	38.014	0.3021***	10.547
LGFCF	0.0087***	7.893	0.8952***	42.156
LGPR	0.0215***	12.634	0.8743***	51.204

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. CUP-FM refers to Continuously Updated Fully Modified estimation, while CUP-BC denotes Continuously Updated Bias-Corrected estimation.

In contrast, major economic indicators, including FDI, GDP, GFCF, and GPR, display a statistically significant positive association with CO_2 emissions. Specifically, a 1% increase in FDI is associated with estimated rises in emissions of 0.20% and 0.34%, according to the CUP-FM and CUP-BC estimations, respectively. Similar trends are observed for GDP (0.02% and 0.30%), GFCF (0.009% and 0.90%), and GPR (0.02% and 0.87%). These findings imply that although economic and geopolitical developments may drive growth, they simultaneously present challenges to environmental sustainability if not accompanied by appropriate mitigation measures.

Table 8 reports the results of the robustness checks conducted using the CCEMG and AMG estimation techniques, aimed at validating the reliability of the findings derived from the CUP-FM and CUP-BC estimators. The results consistently demonstrate an inverse relationship between renewable energy investment and CO_2 emissions, as indicated by the statistically significant negative coefficients of −0.2751 (CCEMG) and −0.2853 (AMG). These findings highlight the crucial role of renewable energy expansion in mitigating environmental degradation and advancing the transition toward a low-carbon economy within the ASEAN region.

Table 8. Robustness analysis result.

Variables	CCEMG Coefficient	t-stat	p-value	AMG Coefficient	t-stat	p-value
LREI	−0.2751**	−0.1902	0.020	−0.2853***	−0.2156	0.008
LGFI	−0.2614**	−1.2011	0.005	−0.2011**	−0.2105	0.038
LFDI	−0.4023*	1.7543	0.085	−0.6501***	−1.4552	0.002
LGDP	0.3154**	1.8321	0.011	0.3887***	1.9256	0.000
LGFCF	0.2859***	4.3875	0.000	0.2194**	1.1325	0.024
LGPR	0.1453*	8.5123	0.090	0.2651*	0.5351	0.063
Wald	–	32.4512	0.000	–	14.6541	0.000

Note: ***, **, * represent significance at 1%, 5%, and 10% levels, respectively. CCEMG = Common Correlated Effects Mean Group. AMG = Augmented Mean Group.

Similarly, GFI exhibits a negative relationship with carbon emissions across both estimation models, reflected in coefficients of −0.2614 (CCEMG) and −0.2011 (AMG), respectively. These results emphasize the critical role of financial mechanisms in advancing environmentally sustainable initiatives, such as clean energy infrastructure, emissions-reducing technologies, and green innovation. The FDI also demonstrates a negative influence on CO_2 emissions, with coefficient estimates of −0.4023 in the CCEMG model and −0.6501 in the AMG model. This indicates that FDI, when directed towards environmentally responsible sectors, may facilitate technology transfer, foster energy efficiency, and support the deployment of low-carbon solutions, thereby reducing emissions. Conversely, GDP and GFCF demonstrate positive and statistically significant impacts on CO_2 emissions across both models. The GDP coefficients are 0.3154 (CCEMG) and 0.3887 (AMG), while the GFCF coefficients are 0.2859 and 0.2194, respectively. These findings indicate that while economic growth and capital accumulation contribute to economic development, they may simultaneously exacerbate environmental degradation if not complemented by the implementation of green policy frameworks and the adoption of cleaner production practices.

The GPR is likewise found to exhibit a positive relationship with carbon emissions, as indicated by the coefficients of 0.1453 (CCEMG) and 0.2651 (AMG). This finding suggests that heightened geopolitical uncertainty may hinder the advancement of sustainable energy transitions, increasing dependence on fossil fuels and delaying the adoption of climate-resilient strategies. Overall, the robustness checks conducted using the CCEMG and AMG estimators demonstrate a high degree of consistency with the primary results obtained from the CUP-FM and CUP-BC methods. The consistency in the direction and statistical significance of the coefficients across different estimation techniques reinforces the empirical validity of the analysis. Collectively, these results reaffirm the environmental benefits of renewable energy investment and green finance, while highlighting the complex interrelationship between economic development, foreign capital flows, and geopolitical stability in influencing the trajectory of carbon emissions in ASEAN economies.

A causal framework illustrating the directional relationships between key economic and environmental variables, namely CO_2 emissions, REI, GFI, FDI, GDP, GFCF, and GPR, is presented in Table 9. The test results, based on the Dumitrescu and Hurlin (2012), the heterogeneous panel causality framework provides evidence of both unidirectional and bidirectional causal linkages among the variables.

Several unidirectional causal relationships are identified, indicating that changes in one variable influence another without reciprocal feedback. Specifically, a unidirectional causality from GDP to CO_2 emissions is observed, suggesting that economic growth directly contributes to environmental degradation. Likewise, green finance is found to Granger-cause CO_2 emissions, implying that fluctuations in the scale or intensity of green financing activities may affect environmental outcomes. A one-way causal relationship is also detected from FDI to GDP, emphasizing the role of foreign investment in promoting economic growth. Furthermore, FDI is found to Granger-cause GFCF, indicating that increases in foreign capital inflows can have a direct impact on domestic capital formation.

Table 9. Results of the Dumitrescu and Hurlin (2012) heterogeneous panel causality test.

Variables	LCO_2	LREI	LGFI	LFDI	LGDP	LGFCF	LGPR
LCO_2	–	3.452[c]	4.210[a]	1.960	4.680[a]	3.450	4.570[a]
		[1.752]	[2.850]	[−0.650]	[7.010]	[2.010]	[3.720]
		(0.082)	(0.001)	(0.432)	(0.000)	(0.145)	(0.000)
LREI	6.210[c]	–	5.200[a]	3.050[b]	2.840	1.900	3.670
	[5.620]		[3.780]	[1.940]	[0.830]	[0.930]	[2.870]
	(0.065)		(0.000)	(0.032)	(0.157)	(0.350)	(0.091)
LGFI	4.210[a]	5.300	–	1.870	1.620	4.510[a]	2.520
	[2.740]	[3.950]		[−0.430]	[−0.750]	[4.510]	[2.510]
	(0.001)	(0.530)		(0.652)	(0.448)	(0.000)	(0.401)
LFDI	3.840[b]	4.720[a]	4.100[a]	–	5.010[a]	2.620	2.700
	[2.510]	[3.840]	[2.920]		[3.680]	[2.640]	[2.710]
	(0.025)	(0.000)	(0.003)		(0.000)	(0.570)	(0.640)
LGDP	7.010[a]	4.010	4.670[a]	8.110	–	8.530[a]	3.630[b]
	[3.720]	[2.560]	[3.160]	[7.650]		[8.530]	[2.130]
	(0.000)	(0.110)	(0.001)	(0.002)		(0.000)	(0.031)
LGFCF	4.420[a]	4.110[b]	5.010[a]	8.610[a]	8.210	–	1.730
	[2.910]	[2.430]	[3.850]	[8.630]	[8.240]		[−0.930]
	(0.003)	(0.020)	(0.000)	(0.000)	(0.002)		(0.350)
LGPR	3.550[b]	4.020	3.930	1.450	3.820	1.460	–
	[1.950]	[2.730]	[3.940]	[1.460]	[3.830]	[1.470]	
	(0.045)	(0.350)	(0.850)	(0.065)	(0.050)	(0.070)	

Note: The null hypothesis assumes no causality. The first value represents the W-statistic, the second denotes the Z-statistic, and the third corresponds to the p-value. Significance levels are indicated as follows: [a] significant at 1%, [b] at 5%, and [c] at 10%.

Bidirectional causal relationships, on the other hand, are indicative of dynamic interdependence. The results reveal a two-way causality between CO_2 emissions and variables such as GFI, GDP, and GPR. This suggests that not only do these economic indicators affect emission levels, but environmental performance may also, in turn, influence these macroeconomic variables. Moreover, a bidirectional causal relationship is identified between REI and CO_2 emissions, highlighting the critical feedback mechanism between clean energy investments and environmental sustainability. This finding underscores the strategic significance of advancing renewable energy development as a key component of carbon mitigation efforts within ASEAN countries. In conclusion, the existence of both unidirectional and bidirectional causal linkages between environmental and economic indicators provides meaningful insights for policymakers. These findings underscore the necessity of integrating environmental considerations into macroeconomic and investment planning. To foster sustainable development and reduce carbon emissions, future policy frameworks should be designed with careful attention to the direction and nature of these causal interactions.

3.2. Discussions

The findings of our study highlight a strong relationship between renewable energy investment and the advancement of carbon neutrality within the ASEAN region. The results indicate that greater allocation of financial resources toward renewable technologies substantially contributes to the reduction of greenhouse gas emissions. This dynamic is particularly significant in the ASEAN context, where energy demand is continually increasing alongside a persistent dependence on fossil fuels. As environmental regulations and carbon pricing mechanisms elevate the costs associated with conventional energy sources, renewable energy alternatives have become increasingly favorable from both economic and environmental perspectives.

These results are consistent with existing empirical evidence from other global regions, including the G20 economies (Chien, 2023; De La Peña et al., 2022; Iqbal et al., 2021), where renewable energy is identified as a pivotal component of emission reduction strategies. As shown in Table 10, our findings are largely consistent with OECD, BRICS, and G20 contexts, reinforcing the universal role of renewable investment and green finance in mitigating emissions. However, the inclusion of geopolitical risk provides novel insights into ASEAN's unique vulnerabilities.

Table 10. Comparison of findings with prior studies.

Variable	Our Study (ASEAN)	OECD (Zhang, 2022)	BRICS (Dong et al., 2023)	G20 (Chien, 2023)
REI $\rightarrow$ CO_2	Negative	Negative	Negative	Negative
GFI $\rightarrow$ CO_2	Negative	Negative	Mixed	Negative
GDP $\rightarrow$ CO_2	Positive	Positive	Positive	Positive
FDI $\rightarrow$ CO_2	Positive	Mixed	Positive	Positive
GPR $\rightarrow$ CO_2	Positive	Not studied	Positive	Limited

Within ASEAN, the deployment of solar, wind, hydro, and geothermal energy technologies offers viable, low-carbon alternatives to conventional sources such as coal and oil. Furthermore, renewable technologies such as biomass provide additional mitigation potential by enabling the capture and repurposing of atmospheric CO_2 for industrial applications, including biofuel production. The broader adoption of such technologies can reduce dependence on carbon-intensive energy sources and strengthen long-term energy security. Our study further identifies a significant negative relationship between green finance and carbon emissions, underscoring the essential role of financial systems in promoting environmental sustainability. By channeling capital toward climate-resilient infrastructure, improvements in energy efficiency, and low-carbon innovations, green finance creates conditions that support the transition to a more sustainable economic model. This finding is consistent with the work of Chin et al. (2022), Liu et al. (2022), and Udeagha and Ngepah (2023), who emphasize the necessity of incorporating green finance mechanisms into national development strategies. Within the ASEAN context, where many countries are in the process of expanding their financial infrastructures, the effective mobilization of green capital constitutes a critical step toward realizing both national and regional climate objectives.

Beyond emissions mitigation, green financing plays a multidimensional role in promoting sustainable development. It supports cleaner technologies, enhances institutional capacities, and encourages the transformation of traditional economic sectors. Nevertheless, its effectiveness is contingent upon the maturity of financial institutions, regulatory frameworks, and policy alignment. While more developed ASEAN member states have demonstrated success in implementing green financial instruments, less-developed economies may require greater international cooperation, capacity building, and institutional reform to realize similar outcomes.

Conversely, the positive relationships observed between economic growth indicators (i.e., GDP, FDI, and GFCF) and CO_2 emissions highlight the environmental trade-offs associated with rapid economic development. These results are consistent with previous studies conducted within the G20 context (Chen et al., 2024; Zhang, 2022), concluding that unchecked industrial expansion and infrastructure development can intensify environmental degradation when sustainability safeguards are lacking. In ASEAN, where economic growth remains a primary policy objective, this dynamic poses a critical challenge to climate-aligned development. Achieving a balance between growth and environmental responsibility requires integrated policy frameworks that internalize environmental costs and promote sustainable investment practices.

The influence of geopolitical risk also emerges as a significant factor in the region’s environmental performance. Our study indicates that geopolitical uncertainty tends to exacerbate carbon emissions, possibly due to shifts in energy security priorities and resource allocation under unstable political conditions. These results corroborate findings by Hassan et al. (2023) and Lau et al. (2023), who suggest that nations facing geopolitical disruptions often revert to carbon-intensive energy sources as a defensive measure. In ASEAN, this trend is particularly relevant, given the region's exposure to maritime disputes, political volatility, and shifting global alliances. However, such risks may also provide impetus for energy diversification and increased investment in domestically produced renewables.

In addition, the results from the Dumitrescu & Hurlin (2012) heterogeneous panel causality analysis reveal intricate interdependencies between economic and environmental variables. The detection of bidirectional causality between CO_2 emissions and renewable energy investment, green finance, GDP, and geopolitical risk indicates the existence of dynamic feedback mechanisms. For instance, increased investments in renewables can reduce emissions, which in turn enhances investor confidence and stimulates further clean energy deployment. Simultaneously, the presence of unidirectional causal relationships, such as from FDI to GDP or from green finance to CO_2 emissions, demonstrates the pivotal influence of economic and financial instruments in shaping environmental outcomes. These insights highlight the necessity for targeted investment policies that not only stimulate economic growth but also support long-term environmental sustainability. Integrating environmental considerations into fiscal, monetary, and trade policy frameworks could further amplify the positive impacts of such interventions.

Collectively, the findings of this study provide several important implications for policymakers in the ASEAN region. They emphasize the critical need to intensify investments in renewable energy and green finance, while concurrently addressing the environmental risks linked to economic growth and political instability. Policymakers should prioritize the creation of enabling environments for sustainable finance, the institutionalization of climate-aligned development plans, and the strengthening of regional cooperation frameworks. Such efforts will be critical to advancing a resilient, inclusive, and low-carbon development trajectory for the ASEAN region in the decades to come.

4. Conclusions

We examined the impacts of renewable energy investment, green finance, and geopolitical risk on carbon emissions in ASEAN countries, employing advanced second-generation panel estimation techniques, namely the CUP-FM and CUP-BC methods, applied to data covering the period from 2001 to 2023. The empirical results provide strong evidence that both renewable energy investment and green finance are crucial in reducing carbon emissions throughout the region. These findings highlight the strategic importance of clean energy deployment and sustainable financial flows as foundational elements of ASEAN's transition toward a low-carbon economy. Moreover, the results align with global evidence about emphasizing the transformative potential of renewable technologies in addressing environmental challenges while enhancing economic resilience.

In contrast, economic growth indicators, specifically foreign direct investment, gross domestic product, and gross fixed capital formation, exhibit a positive association with increasing CO_2 emissions. This indicates that prevailing patterns of economic expansion in ASEAN continue to depend significantly on carbon-intensive industries, thereby underscoring a fundamental tension between development objectives and environmental sustainability. The study further identifies geopolitical risk as a significant factor influencing emissions levels; heightened geopolitical uncertainty is associated with increased reliance on fossil fuels and a reduced capacity to advance renewable energy adoption. This dynamic reflects the vulnerability of energy transition pathways to external shocks, particularly in politically or economically sensitive environments. Causality analysis reveals both unidirectional and bidirectional relationships between the key variables, offering deeper insights into the structural interdependencies of the ASEAN energy–economy–environment nexus. Of particular significance is the bidirectional causality between renewable energy investment and CO_2 emissions, which suggests a reinforcing cycle in which greater clean energy deployment leads to emissions reductions, while escalating environmental concerns stimulate further investment in renewable technologies. Such feedback mechanisms underscore the importance of sustained and coordinated policy action in catalyzing long-term change.

These findings generate several important policy implications. ASEAN governments are urged to institutionalize coherent and stable green finance frameworks capable of mobilizing long-term investments into renewable energy and climate-aligned sectors. This includes the formulation of harmonized green finance taxonomies, the simplification of regulatory procedures, and the provision of fiscal and financial incentives, such as green bonds, concessional lending, and tax exemptions, to enhance investor confidence and reduce capital costs for sustainable projects. Moreover, public–private collaboration should be expanded through structured partnerships that facilitate risk-sharing and project scalability, particularly for large-scale infrastructure. Incorporating geopolitical risk assessments into national energy planning will also be essential, as will strengthening regional cooperation through initiatives such as energy grid integration, cross-border power trading, and collective investment platforms for clean energy. Establishing and deepening regional green capital markets is likewise critical. A harmonized approach to green financial instruments and the development of innovative mechanisms, such as emissions trading systems and carbon pricing frameworks, can increase cross-border investment flows and enhance ASEAN's overall financial capacity to achieve its sustainability goals. A crucial policy implication is the need to decouple economic growth from CO_2 emissions. This can be achieved through (i) carbon pricing and emissions trading systems that internalize environmental costs, (ii) targeted incentives to redirect FDI toward renewable and low-carbon sectors, (iii) subsidies and tax relief for renewable energy projects, and (iv) promotion of energy efficiency measures across industrial sectors. These policies enable ASEAN economies to sustain growth without proportionately increasing emissions.

This study adds to the expanding body of literature on climate economics and sustainable development in Southeast Asia. By empirically illustrating the interrelated roles of renewable energy, green finance, and geopolitical stability in influencing environmental outcomes, it provides important insights for policymakers, investors, and development practitioners. Attaining carbon neutrality in the ASEAN region will necessitate a multidimensional approach that harmonizes economic aspirations with ecological stewardship, underpinned by inclusive, forward-looking, and regionally coordinated policy frameworks.

Nonetheless, our research is subject to certain limitations. Data constraints limit the inclusion of additional sector-specific and institutional variables, which may have provided a more nuanced understanding of country-level dynamics. Furthermore, the proxies used for green finance and geopolitical risk, while informative, may not fully capture variations in implementation quality, governance, or market behavior across the region. Future research should explore more disaggregated and dynamic indicators of green investment and policy effectiveness, integrate environmental, social, and governance metrics, and examine the role of financial innovation, such as digital green finance and carbon trading, in advancing the low-carbon transition. A more granular sectoral analysis and incorporation of institutional strength indicators could also enhance the explanatory power of future models.

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