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Renewable Energy Consumption and Economic Growth: Empirical Evidence from ASEAN Countries

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ABSTRACT

This paper investigates the nexus between renewable energy consumption, economic growth, and carbon emissions in ASEAN-9 from 2000 to 2024 using a nonlinear panel ARDL framework that accounts for heterogeneity, asymmetries, and regional spillovers. The dataset combines renewable energy shares, GDP, CO_2 intensity, foreign direct investment, and inflation. Results reveal pronounced cross-country differences. Malaysia shows rapid adjustment, with renewable expansions supporting growth while contractions impose disproportionately high costs. Singapore exhibits contractionary effects from renewable adoption, reflecting structural constraints and high integration costs. Indonesia and Myanmar also converge, but outcomes remain sensitive to policy credibility and financial conditions. At the regional level, the panel confirms long-run convergence and significant cross-sectional dependence, underscoring exposure to common shocks. Sub-sample analysis points to a post-2010 soft decoupling of growth from emissions, coinciding with major policy shifts. The findings highlight the need for credible national frameworks and deeper financial markets, alongside ASEAN-wide cooperation on incentives, grid integration, and pooled financing. Renewables must be positioned not as an environmental add-on but as a central driver of industrial and regional strategy.

Keywords: Renewable energy consumption; Economic growth; ASEAN economies; Panel NARDL; Asymmetric effects; Foreign direct investment (FDI); Inflation; Carbon emissions; Sustainable development; Energy policy.

INTRODUCTION

Economic growth in ASEAN has accelerated over the past two decades, driven by rapid industrialisation, urbanisation, and rising energy demand. This trajectory has lifted millions out of poverty and strengthened regional integration, but it has also deepened dependence on fossil fuels, resulting in higher carbon emissions, energy insecurity, and greater vulnerability to climate shocks (Tran, Bui, & Vo, 2024). The region therefore faces a pressing dilemma: how to sustain robust growth while reducing environmental degradation.

Renewable energy consumption (REC) is often presented as part of the solution. Beyond lowering carbon intensity, REC can stimulate new industries, create jobs, attract foreign investment, and enhance energy security. These benefits align with several Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action). Yet, whether REC can deliver these outcomes in the ASEAN context is not straightforward. Institutional diversity, uneven infrastructure, and divergent policy frameworks across the region may shape the effectiveness of renewable adoption (Kostakis, 2024).

The empirical evidence on the REC–growth–emissions nexus remains mixed. Studies in emerging economies often find that REC supports long-run growth while reducing emissions (Sun, Razzaq, & Scholtens, 2022). Other work, however, shows that benefits materialise only after consumption passes a threshold or when supported by strong institutions and financial systems (Nathaniel & Khan, 2020). Within ASEAN, the results are inconsistent: some evidence points to long-run environmental gains in high-income members such as Singapore, while others remain on an upward emissions trajectory despite modest renewable deployment (Tran, Bui, & Vo, 2024). These contrasting findings raise the question of whether renewables can play a transformative role across such a heterogeneous region.

Although the literature has expanded, several limitations remain. Many ASEAN-focused studies are dated, often relying on pre-2018 data that exclude recent renewable breakthroughs such as Vietnam's solar boom and Indonesia's biofuel expansion. Others adopt aggregate measures of energy use rather than renewable-specific indicators, which makes it difficult to isolate the unique structural role of renewables. In addition, linear approaches dominate the literature, even though theoretical frameworks such as the Environmental Kuznets Curve and endogenous growth theory suggest that renewable impacts are unlikely to be uniform or symmetric (Kostakis, 2024). Finally, ASEAN economies are increasingly interconnected through trade, investment, and energy flows, yet few studies explicitly account for cross-sectional dependence or regional spillovers.

This study builds on these debates by examining the dynamic relationship between renewable energy consumption, economic growth, and carbon emissions in ASEAN-9 over the period 2000–2024. Advanced econometric techniques are employed, including nonlinear panel ARDL and asymmetric modelling, supported by robustness checks for cross-sectional dependence. The analysis distinguishes between short-run fluctuations and long-run equilibria, while explicitly testing for threshold and asymmetric effects. By focusing on REC rather than total energy use, the study isolates the distinctive role of renewables in shaping both growth and environmental outcomes.

The contributions are threefold. First, the paper provides updated evidence using recent data that capture ASEAN's evolving renewable transition. Second, it applies asymmetric and threshold-based econometric techniques that better reflect cross-country heterogeneity and regional spillovers. Third, it offers policy-relevant insights into how ASEAN can design coordinated renewable strategies that reconcile economic growth with environmental sustainability.

LITERATURE REVIEW

This The debate over whether renewable energy can drive economic growth while reducing environmental degradation has intensified in recent years. For some scholars, renewables represent a catalyst for innovation, industrial upgrading, and long-run sustainability; for others, their benefits remain conditional, uneven, and in some cases, elusive. ASEAN sits at the centre of this debate, as its economies combine rapid growth with rising emissions and ambitious but uneven energy transitions. Against this background, this chapter reviews the main theoretical foundations, synthesises empirical evidence from global and regional studies, and highlights the critical gaps that this study seeks to address.

Theoretical Foundation

Renewable energy can influence growth through several channels. In endogenous growth perspectives, cleaner technologies raise productivity by reducing input volatility, lowering energy import exposure, and inducing complementary capital deepening and learning-by-doing. These mechanisms imply that renewable uptake may support output not merely via substitution from fossil fuels, but through innovation spillovers and improved energy security. At the same time, transition costs—grid integration, intermittency management, and policy uncertainty—can dampen short-run performance, particularly where institutions and financial systems are weak. The Environmental Kuznets Curve (EKC) framework adds a further layer: environmental pressure typically rises at early stages of development and eases once income and policy capacity reach critical levels, implying that the growth–emissions–energy linkage is unlikely to be linear across space or time. Taken together, these theories motivate asymmetric and threshold responses: positive expansions of renewables may crowd-in investment and efficiency, while contractions (or poorly sequenced policies) can generate disproportionate adjustment costs.

For ASEAN, theoretical priors must be read through the lens of heterogeneity. Differences in grid readiness, market design, and policy credibility mean that equivalent changes in renewable energy consumption (REC) can transmit differently across economies. The implication is straightforward: the region provides a natural laboratory where non-linearity, country effects, and regional spillovers are not nuisances but key features to be modelled.

Empirical Evidence

Empirical studies on the renewable energy–growth–environment nexus have expanded significantly, yet findings remain far from uniform across countries, methods, and timeframes. At the global level, many works support the renewable energy–led growth hypothesis, highlighting that renewable energy fosters GDP growth by enhancing energy security, stimulating technological innovation, and reducing dependence on fossil imports. For instance, Bhuiyan et al. (2022) show that renewable adoption generally stimulates economic growth across developed and developing economies, though the magnitude varies depending on institutional capacity and financial development. Similarly, Razzaq et al. (2023) demonstrate that renewable deployment, when accompanied by green innovation, substantially reduces emissions, although the effect is contingent on adoption scale, industrial structure, and regulatory credibility. Nguyen et al. (2023) further confirm that renewables are linked to long-run decarbonisation, but warn that their growth impacts may be limited in economies with fragile grids or low absorptive capacity. These findings collectively reinforce that renewables can support both growth and environmental goals, but outcomes are strongly mediated by country-specific institutional and structural contexts.

Evidence from emerging economies provides additional nuance. Sun, Razzaq, and Scholtens (2022) demonstrate that renewable energy and globalisation reduce emissions asymmetrically, with negative shocks exerting stronger adverse effects than the positive benefits of expansions. Nathaniel and Khan (2020) find that renewable energy improves environmental quality in emerging markets, but only when supported by trade openness, financial integration, and governance stability. In contrast, Bhattacharya and Paramati (2021) show that renewables can increase short-run energy costs in developing countries with inadequate infrastructure, suggesting that gains are conditional on complementary reforms. Recent Latin American and African studies echo this pattern, confirming that renewable energy can either catalyse industrial upgrading or exacerbate volatility, depending on policy frameworks and macroeconomic resilience (Moreno, Medina, and Palma-Behnke, 2024). These studies highlight that the net effect of renewables is highly context-dependent, with significant variation across different stages of development and institutional quality.

ASEAN-specific studies reflect similar heterogeneity. Tran (2024) finds that renewable energy consumption reduces CO_2 emissions in the long run, though short-run effects remain weak, with several middle-income economies still on the rising side of the EKC. Rahman et al. (2024) provide evidence of renewable energy Granger-causing GDP in some ASEAN economies (Indonesia, Malaysia, Singapore) but not in others (Thailand, the Philippines), pointing to uneven structural transformation across the region. Kostakis (2024) show that renewable energy can simultaneously foster growth and emissions reduction, but only in economies with strong governance and financial openness. More recently, Nam et al. (2024) demonstrate that Vietnam exhibits threshold effects, where renewable adoption supports growth only after crossing a critical share in the energy mix, while below that level, costs dominate. Zhong et al. (2025) also emphasise that ASEAN's fragmented energy infrastructure and inconsistent policy frameworks delay the benefits of renewable integration, despite ambitious national targets. Together, these findings underscore the difficulty of applying uniform policy prescriptions in a region marked by wide diversity in resource endowments, institutional arrangements, and economic structures.

Another recurring theme in the empirical literature is the importance of macroeconomic and financial conditions in mediating renewable outcomes. High inflation, volatile exchange rates, and weak financial systems raise project costs and delay investment, eroding potential growth benefits. Moreno and friends (2024) confirm that financial depth and regulatory credibility significantly influence the effectiveness of renewable investment in emerging Asia. Similarly, studies on cross-country capital flows show that renewable-focused foreign direct investment (FDI) supports technology transfer and green infrastructure, but reversals during crises create financing gaps that undermine long-term projects (Razzaq et al., 2023; Tran, 2024). This cyclical sensitivity is particularly relevant for ASEAN, where external shocks such as the 1997 Asian Financial Crisis, the 2008 Global Financial Crisis, and the COVID-19 pandemic have repeatedly disrupted energy investment cycles.

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Despite these contributions, three critical limitations persist in the ASEAN literature. First, many studies rely on datasets that end before 2018, thereby excluding the recent surge of renewable investments such as Vietnam's solar boom, Indonesia's biofuel initiatives, and Thailand's floating solar expansion. Second, the majority of existing analyses employ aggregate energy consumption instead of renewable-specific measures, masking the distinct structural contribution of renewables to both growth and emissions. Third, limited attention has been paid to non-linear and asymmetric dynamics, even though evidence from other regions confirms their importance for understanding the uneven impact of renewable shocks (Sun et al., 2022; Nam et al., 2024). Finally, only a few studies account for cross-sectional dependence and spillovers, despite ASEAN economies being closely linked through trade, investment, and exposure to global energy price cycles (Zhong et al., 2025). Ignoring these interdependencies risks underestimating the extent to which regional shocks and spillovers shape renewable energy outcomes.

Overall, the empirical evidence reveals that while renewable energy has the potential to support both growth and environmental goals, its effectiveness in ASEAN depends on institutional strength, macroeconomic stability, and cross-border coordination. This mixed and conditional evidence justifies the need for updated and methodologically robust analysis that captures heterogeneity, asymmetry, and regional interdependence, particularly given the region's ongoing transition towards clean energy.

Research Gap

Despite a growing body of research on the renewable energy–growth–environment nexus, important gaps remain in the ASEAN context. A recurring limitation is the reliance on outdated datasets. Much of the empirical evidence ends prior to 2018, thereby excluding recent developments such as Vietnam's rapid solar expansion, Indonesia's biofuel programmes, and Thailand's deployment of floating solar technologies (Tran, Bui, & Vo, 2024). These initiatives have significantly reshaped the region's energy landscape and their omission means that earlier studies may not capture the full dynamics of ASEAN's transition. Without incorporating these recent shifts, it is difficult to assess whether renewable energy is evolving into a structural driver of growth or remains marginal in practice.

A second concern is the use of aggregate energy data as proxies for renewable consumption. Many studies continue to rely on total energy or electricity use, which inevitably obscures the specific contribution of renewables. As Bhuiyan et al. (2022) argue, such aggregation risks underestimating the distinctive technological, environmental, and economic implications of renewable deployment. Given that renewables often interact differently with capital formation, labour markets, and environmental outcomes compared to fossil fuels, the absence of renewable-specific measures weakens the explanatory precision of existing models.

Third, the methodological orientation of much of the literature remains strongly linear. Standard econometric frameworks assume that expansions and contractions in renewable energy affect growth in a symmetric fashion. This assumption is questionable in the ASEAN setting, where structural rigidities, adjustment costs, and intermittency management can lead to markedly different impacts depending on the direction of change. Theoretical insights from endogenous growth models and the Environmental Kuznets Curve reinforce the likelihood of non-linearity, where benefits may only materialise once consumption surpasses certain thresholds or when supported by strong institutional capacity (Sun, Razzaq, & Scholtens, 2022; Kostakis, 2024). Yet empirical tests of such asymmetries remain rare.

Finally, the regional interdependence of ASEAN economies is often under-acknowledged. The bloc is increasingly integrated through trade, foreign investment, and exposure to global energy shocks, which suggests that energy and growth outcomes in one country can generate spillovers in others. Ignoring these cross-sectional linkages risks biased estimates and overlooks the collective nature of the ASEAN energy transition (Kostakis,2024). This omission is especially problematic for policy, since national energy strategies are often shaped by regional markets and financing conditions.

This study directly addresses these gaps. By employing renewable-specific data for ASEAN-9 from 2000 to 2024, it captures the structural role of renewables beyond aggregated energy patterns. By applying nonlinear and asymmetric modelling, it tests whether positive and negative renewable shocks affect growth differently, and whether threshold effects are present. By incorporating cross-sectional dependence, it also recognises ASEAN's interconnectivity and the potential for regional spillovers. In doing so, this study contributes updated and methodologically robust evidence that clarifies how renewables influence both growth and environmental outcomes, while offering insights into how coordinated regional strategies can support ASEAN's sustainable energy transition.

Theoretical Framework

This study develops a theoretical framework that links renewable energy consumption, economic growth, and environmental outcomes in ASEAN. The framework draws on three core perspectives: endogenous growth theory, the Environmental Kuznets Curve (EKC), and the asymmetric adjustment hypothesis, while also recognising the importance of regional spillovers that characterise ASEAN economies.

From the perspective of endogenous growth theory, renewable energy is viewed as a productivity-enhancing input that stimulates innovation, reduces dependence on imported fossil fuels, and strengthens competitiveness. In this context, economic growth can be modelled as a function of renewable energy alongside foreign direct investment, inflation, and carbon emissions:

$$GDP_{it} = \alpha_i + \beta_1 REC + \beta_2 FDI_{it} + \beta_3 INF_{it} + \beta_4 CO_{2_{it}} + \varepsilon_{it} \qquad (1)$$

where a positive coefficient on REC would imply that renewable adoption contributes to long-run growth through technological spillovers, while negative coefficients on inflation and emissions would capture the costs of macroeconomic instability and environmental degradation.

To complement this, the EKC hypothesis predicts that the relationship between income and emissions is nonlinear, taking the form of an inverted-U. At low levels of income, emissions rise with growth, but at higher income levels structural transformation and regulation gradually reduce environmental pressures. This can be represented as:

$$GDP_{it} = \alpha_i + \theta^+ REC_{it}^+ + \theta^- REC_{it}^- + \beta_2 FDI_{it} + \beta_3 INF_{it} + \beta_4 CO_{2_{it}} + \varepsilon_{it} \qquad (2)$$

where REC^+ captures increases and REC^- captures decreases in renewable energy consumption. Evidence of $\theta^+ \neq \theta^-$ would indicate asymmetric adjustment.

Finally, because ASEAN economies are highly interconnected through trade, investment, and energy markets, the framework also accounts for cross-sectional dependence and common shocks. This ensures that spillover effects—such as oil price volatility or financial crises—are not ignored in the estimation. A factor structure is therefore included in the specification:

$$GDP_{it} = \alpha_i + \theta^+ REC_{it}^+ + \theta^- REC_{it}^- + \beta_2 FDI_{it} + \beta_3 INF_{it} + \beta_4 CO_{2_{it}} + \lambda_i f_t + \varepsilon_{it} \qquad (3)$$

where f_t represents unobserved global or regional shocks and λ_i denotes country-specific exposure to them.

This framework integrates multiple theoretical perspectives into a coherent structure. Endogenous growth theory justifies the role of renewables in driving productivity, the EKC captures the nonlinearity between growth and emissions, and the asymmetric hypothesis reflects the unequal impacts of positive and negative shocks. By also recognising regional interdependence, the framework reflects the realities of ASEAN's integration and provides a solid theoretical basis for the empirical modelling strategy adopted in this study.

Hypotheses Development

The theoretical perspectives reviewed earlier allow us to translate broad conceptual insights into specific testable hypotheses. Endogenous growth theory suggests that renewable energy enhances productivity, stimulates innovation, and contributes positively to long-run development. This leads to the expectation that renewable energy consumption exerts a positive and significant impact on economic growth in ASEAN economies.

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Formally, this can be expressed as:

$$H1: GDP_{it} = \alpha_i + \beta_1 REC + \beta_2 FDI_{it} + \beta_3 INF_{it} + \beta_4 CO_{2_{it}} + \varepsilon_{it}, \quad \beta_1 > 0 \tag{4}$$

In parallel, the Environmental Kuznets Curve (EKC) hypothesis predicts a nonlinear relationship between income and emissions. At lower income levels, growth is expected to intensify pollution, but beyond a certain threshold, structural transformation and environmental regulation reduce emissions. This leads to a second hypothesis that the relationship between growth and carbon emissions in ASEAN follows an inverted-U pattern:

$$H2: lnCO_{2_{it}} = \alpha_0 + \delta_1 lnGDP_{it} + \delta_2 (lnGDP_{it})^2 + \varepsilon_{it}, \quad \delta_1 > 0 \tag{5}$$

Finally, the asymmetric adjustment perspective emphasises that expansions and contractions in renewable energy use may not yield symmetric outcomes. Increases in renewable deployment may deliver incremental growth benefits, while decreases may impose disproportionately larger costs. This leads to the third hypothesis, which can be framed as:

$$H3: lnGDP_{it} = \alpha_i + \theta^+ REC_{it}^+ + \theta^- REC_{it}^- + \gamma X_{it} + \varepsilon_{it}, \quad \theta^+ \neq \theta^- \tag{6}$$

where REC_{it}^+ and REC_{it}^- capture positive and negative shocks in renewable energy consumption, and X_{it} represents the vector of controls such as FDI, inflation, and emissions.

Together, these hypotheses provide a structured foundation for the empirical strategy. H1 evaluates the direct growth contribution of renewable energy, H2 tests whether ASEAN economies are transitioning towards sustainability in line with the EKC, and H3 examines the asymmetric effects of renewable shocks. This framework not only captures linear and nonlinear dynamics but also allows the econometric design to account for heterogeneity, thresholds, and cross-sectional dependence, which are central features of the ASEAN context.

METHODOLOGY

This study investigates the relationship between renewable energy consumption and economic growth in ASEAN-9 countries such as Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam, over the period 2000–2024. Brunei Darussalam is excluded due to severe data limitations in renewable energy consumption and macroeconomic indicators, as well as its hydrocarbon-dominated economic structure, which makes it an outlier relative to other ASEAN economies.

Data Sources and Coverage

A balanced panel dataset is constructed for the nine ASEAN countries covering the years 2000–2024. Renewable energy consumption is measured as the share of renewable energy in total final energy consumption (TFEC). Where data gaps exist in the World Development Indicators (WDI), supplementary data are drawn from the International Renewable Energy Agency (IRENA) to ensure coverage and consistency. Economic output is represented by real GDP (constant 2015 US$). Additional controls include foreign direct investment (net inflows as % of GDP), inflation (annual CPI %), and carbon intensity (CO_2 emissions per unit of GDP).

To improve statistical properties, variables are transformed prior to estimation. Real GDP and carbon intensity are expressed in natural logarithms, foreign direct investment is transformed using the inverse hyperbolic sine (asinh) to handle potential negative and fat-tailed values, and renewable energy consumption is scaled to a unit interval. These transformations normalise distributions and preserve meaningful economic interpretation.

Descriptive Analysis and Multicollinearity Tests

Prior to model estimation, descriptive statistics and multicollinearity diagnostics were conducted to ensure data reliability. Descriptive analysis summarises key patterns, outliers, and distributions within the dataset. Multicollinearity tests help to detect excessive correlations among independent variables, which could distort regression results. These preliminary steps ensure the model is robust and the variables are suitable for estimation.

Panel Unit Root Test

To evaluate the stationarity of the variables, panel unit root tests were employed. The general form of the test equation (1) is given below:-

$$\Delta Y_{it} = \alpha_i + \rho Y_{it-1} + \sum_{j=1}^{p} \gamma_j \Delta Y_{it-j} + \epsilon_{it} \quad (8)$$

Where:

Y_{it}: The variable of interest (e.g., GDP, REC, FDI, INF,CO_2) for country *i* at time *t*.

ΔY_{it}: First-difference of the variable of interest for country *i* at time *t*.

α_i: Country-specific fixed effect.

ρ: Parameter indicating the presence of a unit root.

p: Number of lags.

γ_j: Coefficient of the lagged difference term.

ϵ_{it}: Error term.

The Levin, Lin, and Chu (LLC) test (Levin et al., 2002) is applied under the assumption of a common unit root process. If the LLC test yields inconclusive results, the Im, Pesaran, and Shin (IPS) test (Im et al., 2003) is employed, which allows for heterogeneity. To reinforce robustness, the Hadri LM test is also conducted, where the null hypothesis indicates stationarity.

Equation (2) represents the deterministic trend specification:

$$Y_{it} = \alpha_i + \delta_i t + \epsilon_{it} \quad (9)$$

Where α_i captures individual fixed effects, $\delta_i t$ is the time trend, and ϵ_{it} represents the idiosyncratic error term.

Asymmetric Panel NARDL

In empirical analysis, the symmetric Panel ARDL provides a useful baseline to examine the relationship between renewable energy consumption and economic growth. In general, the Panel ARDL equation can be expressed as follows:

$$\Delta y_{it} = \emptyset_i \left(y_{i,t-1} - \emptyset' X_{i,t-1} \right) + \sum_{j=1}^{pi} \lambda_{ij} \, \Delta y_{i,t-1} + \sum_{j=1}^{zi} \Gamma'_{ij} \Delta x_{i,t-1} + \mu_i + \varepsilon_{it} \quad (10)$$

where y_{it} denotes economic growth, $X_{i,t}$ represents renewable energy consumption and other control variables, $\emptyset'$ captures the speed of adjustment while the short-run and long-run dynamics are reflected in the lagged differences and lagged levels respectively.

However, this specification assumes linearity and uniform effects, meaning that positive and negative shocks in renewable energy are treated symmetrically across countries. Such an assumption is restrictive, particularly for ASEAN economies that exhibit structural heterogeneity in their energy systems, policy frameworks, and adjustment costs. To address this limitation, the study employs the Panel Nonlinear ARDL (PNARDL) model, which decomposes renewable energy into positive and negative partial sums. This approach allows asymmetric dynamics, whereby expansions and contractions in renewable energy consumption may exert different impacts on economic growth across heterogeneous economies.

Following Shin, Yu, and Greenwood-Nimmo (2014), we employ a nonlinear autoregressive distributed lag (NARDL) model in panel form. This specification is suitable for three reasons: (i) it captures possible asymmetries in the response of growth to renewable-energy shocks, (ii) it allows for cross-country heterogeneity, and (iii) it permits regressors of mixed orders of integration, provided none is I(2).

To allow asymmetric growth responses, renewable energy is split into positive and negative partial sums:

$$RE_{it}^{+} = \sum_{s=1}^{t} \max(\Delta re_{ik}, 0), \quad RE_{it}^{-} = \sum_{s=1}^{t} \min(\Delta re_{ik}, 0) \tag{11}$$

These are the standard partial-sum decompositions used to model nonlinear adjustment.

The nonlinear panel ARDL is then:

$$\Delta y_{it} = \beta_{0i} + \beta_{1i} y_{i,t-1} + \beta_{2i}^{+} re_{i,t-1}^{+} + \beta_{2i}^{-} re_{i,t-1}^{-} + \beta_{3i}' x_{i,t-1} + \sum_{j=1}^{pi} \lambda_{ij} \, \Delta y_{i,t-1} + \sum_{j=1}^{qi} (\gamma_{ij}^{+} \Delta_{i,t-j}^{+} + \gamma_{ij}^{-} \Delta_{i,t-j}^{-}) + \sum_{j=1}^{zi} \Gamma_{ij}' \Delta x_{i,t-1} + \mu_i + \varepsilon_{it} \tag{12}$$

This is the panel analogue of the Shin et al. (2014) NARDL, designed to capture nonlinear asymmetries directly in the conditional mean, not in the variance.

The long-run asymmetric elasticities of growth to renewable energy are:

$$\theta_1^{+} = -\frac{\beta_{2i}^{+}}{\beta_{1i}}, \qquad \theta_1^{-} = -\frac{\beta_{2i}^{-}}{\beta_{1i}}, \tag{13}$$

allowing positive and negative renewable-energy shocks to have different long-run effects on growth.

An error-correction version can be written as:

$$\Delta y_{it} = \tau_i \xi_{i,t-1} + \sum_{j=1}^{pi} \lambda_{ij} \, \Delta y_{i,t-1} + \sum_{j=1}^{pi} \lambda_{ij} \, \Delta y_{i,t-1} + \sum_{j=1}^{qi} (\gamma_{ij}^{+} \Delta RE_{i,t-j}^{+} + \gamma_{ij}^{-} \Delta RE_{i,t-j}^{-}) + \sum_{j=1}^{zi} \Gamma_{ij}' \Delta X_{i,t-1} + \mu_i + \varepsilon_{it} \tag{14}$$

where $\xi_{i,t-1}$ denotes nonlinear long-run equilibrium and $\tau_i < 0$ captures the speed of adjustment.

Estimation Strategy

The The empirical analysis begins with descriptive statistics to summarise the distribution of the variables and highlight cross-country variation. Pearson correlation matrices are then examined to identify simple associations between renewable energy, economic growth, foreign direct investment (FDI), inflation, and carbon intensity. To guard against multicollinearity, variance inflation factors (VIFs) are reported, with all values well below the conventional threshold of 10, confirming that the explanatory variables are not affected by severe overlap.

Having established the basic properties of the data, the next step is to assess the order of integration. Both first- and second-generation panel unit root tests are employed, including Levin–Lin–Chu (LLC), Im–Pesaran–Shin (IPS), and Pesaran's CIPS, the latter allowing for cross-sectional dependence. This ensures that no variable is integrated beyond I(1), which is a fundamental requirement for the application of panel ARDL and NARDL estimators. Long-run relationships are then verified using Pedroni and Westerlund error-correction tests, providing evidence of stable cointegration among the variables.

Estimation proceeds with the nonlinear panel ARDL (NARDL) framework to capture potential asymmetries in the response of growth to renewable energy shocks. Both the Mean Group (MG) and Pooled Mean Group (PMG) estimators are employed. The MG estimator captures full heterogeneity across countries, while the PMG estimator imposes common long-run coefficients but allows short-run dynamics to vary. This distinction is crucial in the ASEAN context, as it tests whether diverse economies share a convergent long-run equilibrium. The choice between MG and PMG is guided by Hausman-type tests, which indicate whether the pooling restriction on long-run coefficients is empirically valid.

Finally, several robustness checks are conducted. These include cross-sectional dependence tests (Pesaran CD), slope heterogeneity diagnostics (Pesaran–Yamagata Δ), winsorisation of extreme values to mitigate the influence of outliers, and sub-sample analysis across decades (2000–2009 vs. 2010–2024) to capture possible structural shifts. Collectively, these procedures ensure that the reported results are not driven by statistical artefacts and that the long-run interpretations are both credible and policy relevant.

RESULTS AND DISCUSSION

Introduction

This section presents and discusses the empirical results of the study. The analysis is divided into several stages. First, the descriptive statistics of the dataset are introduced to show the broad picture of the ASEAN-9 economies. This helps in understanding the structural and macroeconomic diversity of the region. Second, panel unit root tests are conducted to confirm the integration order of the variables. Third, country-level ECM–NARDL results are presented to capture the short-run and long-run dynamics of renewable energy consumption and economic growth. Fourth, panel summary tests are reported to provide a regional perspective. Fifth, residual diagnostics are conducted to ensure model reliability. Sixth, robustness checks are applied to confirm the stability of the results. Finally, the findings are synthesised and linked to theory and policy implications.

The results highlight both the differences and commonalities across ASEAN. The analysis shows that while some economies benefit from renewable energy expansion, others experience adjustment costs. The findings also indicate that foreign direct investment and inflation have country-specific effects on growth. Importantly, evidence of cross-sectional dependence suggests that ASEAN economies are not isolated but respond to common shocks and regional dynamics.

Descriptive Analysis

Table 1 reports the descriptive statistics and multicollinearity results. Real GDP (lnGDP) averages 25.28, with a relatively wide dispersion, reflecting structural income differences among ASEAN countries. Renewable energy consumption (REC) shows a mean of 0.34 with large variation, indicating uneven adoption of renewables. Foreign direct investment (FDI) averages 5.95 but with considerable volatility, consistent with heterogeneous investment flows across the region. Inflation (INF) records a mean of 5.07 with extreme values ranging from –5.99 to 41.51, capturing both deflationary pressures and inflationary shocks. Carbon emissions ($\ln CO_2$) reveal substantial cross-country disparities, with some economies remaining low-carbon while others are highly industrialised.

TABLE 1: Summary of Descriptive Statistics and Multicollinearity Results (ASEAN-9, 2000–2024)

Variable	Obs	Mean	SD	Min	Max
lnGDP	225	25.28	1.53	22.32	27.85
REC	225	0.34	0.28	0.01	1
FDI	225	2.04	0.98	-1.74	4.19
INF	225	5.07	5.8	-5.9	41.51
$\ln CO_2$	225	0.34	1.32	-1.83	2.43

Note:

1. lnGDP and $\ln CO_2$ are expressed in natural logarithms.
2. VIF = Variance Inflation Factor; values below 5 indicate the absence of multicollinearity concerns (Gujarati & Porter, 2009).
3. Obs = number of observations; SD = standard deviation.

Source: Author's estimation

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Multiclonality Test

Based on Table 2, multicollinearity is not a concern. The largest Spearman rank correlations are moderate—$lnGDP–lnCO_2 = 0.675$, $REC–lnCO_2 = −0.6198$, and $REC–lnGDP = −0.5430$—well below common red flags ($|\rho| \geq 0.80$). Consistently, the pooled-OLS variance inflation factors (VIFs) for the regressors are low, ranging from 1.15 to 1.71 with a mean of 1.37, far under the cautionary threshold of 5 (and the problem threshold of 10). Economically, the positive $lnGDP–lnCO_2$ association reflects scale effects, while the negative $REC–lnCO_2$ correlation is consistent with partial decarbonization as renewable penetration rises. The negative REC–lnGDP correlation likely captures between-country composition rather than a within-country trade-off, which the panel model (with dynamics and fixed effects) addresses. Overall, the low VIFs imply no meaningful inflation of standard errors, so coefficients—particularly long-run elasticities and the error-correction speed in PMG/PNARDL—remain interpretable; as a robustness note, we computed VIFs from a static pooled model, and results are unchanged after within demeaning.

TABLE 2: Specimen Correlation

Variables	LNGDP	REC	FDI	INF	lnCO2	VIF	1/VIF
lnGDP	1.0000					-	-
REC	-0.5430	1.0000				1.71	0.58
FDI	-0.3133	-0.0607	1.0000			1.45	0.69
INF	-0.2337	0.2493	-0.1652	1.0000		1.16	0.86
lnCO2	0.6750	-0.6198	0.1922	-0.4086	1.0000	1.15	0.87
Mean VIF						1.37	

Source: Author's estimation

Panel Unit Root Tests

Table 3 reports the panel unit root test results for the variables in both level and first-difference forms. At levels, the results are mixed: lngdp and rec fail to reject the unit root hypothesis under LLC and IPS but are flagged as non-stationary by the Hadri test. In contrast, fdi, inf, and lnco2 are stationary according to LLC and IPS, though the Hadri test again rejects the null of stationarity, reflecting its sensitivity to cross-sectional dependence and heteroskedasticity.

TABLE 3: Panel Unit Root Result

Variable	LLC		IPS Z		Hadri	
	Level	**1st Diff**	**Level**	**1st Diff**	**Level**	**1st Diff**
lnGDP	-0.1821 (0.4278)	-4.7670*** (0.0000)	2.7867 (0.9973)	-6.3901*** (0.0000)	29.9313*** (0.0000)	0.5549 (-0.2895)
REC	3.4078 (0.9997)	-2.3919*** (0.0084)	-0.1795 (0.4288)	-4.3165*** (0.0000)	21.3325*** (0.0000)	3.3307*** (0.0004)
FDI	-3.1103*** (0.0009)	-7.7011*** (0.0000)	-5.2893*** (0.0000)	-9.3113*** (0.0000)	3.5704*** (0.0002)	-3.2710 (0.9995)
INF	-2.7546*** (0.0029)	-9.8789*** (0.0000)	-7.3207*** (0.0000)	-9.6151*** (0.0000)	5.4242*** (0.0000)	-2.0162 (0.9781)
lnCO2	-2.0778** (0.0189)	-4.4200*** (0.0000)	-2.0408** (0.0206)	-7.0856*** (0.0000)	15.2145*** (0.0000)	4.8212*** (0.0000)

Note:

1. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively.
2. Values in parentheses are p-values.
3. LLC and IPS test the null hypothesis of a unit root (H0: non-stationary). Hadri tests the null hypothesis of stationarity (H0: stationary).

Source: Author's Estimation

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When the series are first-differenced, the findings are more consistent. Both LLC and IPS strongly reject the unit root null across all variables at the 1% level, indicating that the differenced series are stationary. The Hadri test yields mixed outcomes, identifying potential non-stationarity in rec and lnco2, though it does not reject stationarity for lngdp, fdi, and inf.

Overall, the combined evidence suggests that the variables lngdp, rec, fdi, inf, and lnco2 are integrated of order one, I(1). This validates the application of panel cointegration and dynamic modelling techniques such as the Panel NARDL, which allow for regressors of mixed integration provided none are integrated beyond I(1).

Country-Level ECM-NARDL Results

Table 4 presents the ECM–NARDL estimates at the country level, and the results reveal significant heterogeneity across ASEAN economies, both in terms of adjustment speed and asymmetric responses to renewable shocks. The error-correction terms (ECT) indicate whether economies converge towards long-run equilibria, while the Wald tests capture asymmetry between positive and negative renewable energy shocks. Together, these results confirm that renewable energy adoption in ASEAN does not follow a uniform pattern but is deeply conditioned by institutional capacity, structural factors, and policy credibility.

In Malaysia, the adjustment speed is the fastest in the sample ($\varphi = -0.662$, $p < 0.05$), confirming strong convergence to long-run equilibrium. Moreover, the Wald test indicates significant asymmetry ($p = 0.000$), with renewable energy expansions supporting growth while contractions have sharper negative impacts. This is consistent with the adjustment cost hypothesis (Sun, Razzaq, & Scholtens, 2022), which suggests that reductions in renewables impose disproportionately larger costs than the incremental benefits of expansions. Malaysia's outcome reflects its relatively stable institutional framework, strong renewable incentives, and expanding solar capacity. As highlighted by Nathaniel and Khan (2020), governance stability and financial depth are key to enabling renewable-led growth. Malaysia demonstrates this dynamic: credible policies and relatively deep financial markets allow renewable expansion to foster productivity, consistent with endogenous growth theory, while contractions erode confidence and deter investment.

TABLE 4: Country-Level ECM-NARDL Estimates

Country	**ECT (φ)**	**θ_REC⁺**	**θ_REC⁻**	**θ_FDI**	**θ_INF**	**θ_lnCO₂**	**Wald Asym p**
Cambodia	-0.07 (0.39)	1.76	3.11	-0.04	0.06	-0.47	0.59
Indonesia	-0.27 (0.00)***	5.83	5.74	-0.12	0.01	0.69	0.97
Lao PDR	-0.01 (0.82)	-49.92	-4.23	1.02	0.01	0.94	0.83
Malaysia	-0.66 (0.04)**	1.37	6.08	0.09	-0.01	0.59	0.00
Myanmar	-0.18 (0.06)*	1.30	-1.62	0.17	-0.01	0.46	0.17
Philippines	-0.12 (0.19)	28.58	-1.17	0.20	0.08	-0.83	0.29
Singapore	-0.32 (0.00)***	-2.77	71.12	0.21	0.02	-0.65	0.00
Thailand	-0.04 (0.75)	11.94	-22.84	0.50	0.10	-0.38	0.79
Vietnam	-0.00 (1.00)	-206.62	1531.51	-140.23	-5.75	-148.04	1.00

Notes: ECT (φ) p-values in parentheses. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Wald tests $\theta^+ = \theta^-$.

Source: Author's estimation

Singapore presents a strikingly different case. The ECT is significant ($\varphi = -0.323$, $p < 0.01$), showing convergence, but the asymmetry pattern is reversed. Positive renewable shocks are contractionary while negative shocks appear expansionary. This outcome reflects Singapore's unique structural conditions: a small, land-constrained economy heavily dependent on imported energy. Renewable expansion often entails high costs and limited scalability, which may displace more efficient conventional sources and temporarily weigh on output. This result resonates with the findings of Zhong et al. (2025), who noted that fragmented or costly renewable adoption can undermine competitiveness in economies with constrained resources. In theoretical terms, Singapore illustrates the limits of endogenous growth benefits in the absence of sufficient absorptive capacity and infrastructure.

Indonesia also shows significant adjustment ($\varphi = -0.268$, $p < 0.01$), confirming convergence to long-run equilibrium. Both positive and negative renewable shocks are large and positive ($\theta^+ = 5.83$, $\theta^- = 5.74$), suggesting that renewable expansion and contraction move growth in the same direction. While this may seem counterintuitive, it reflects the transitional nature of Indonesia's energy sector, where biofuels and hydro expansion create growth opportunities, but volatility in subsidies and global palm oil prices can also distort outcomes. This echoes Bhattacharya and Paramati (2021), who argued that renewable gains in developing economies are conditional on stable policy frameworks. Indonesia's result suggests that while long-run equilibrium is achievable, the direction and magnitude of renewable effects remain highly sensitive to policy stability and global market dynamics.

Myanmar records weaker but still significant convergence ($\varphi = -0.182$, $p < 0.10$), with REC expansions ($\theta^+ = 1.30$) supporting growth but contractions ($\theta^- = -1.62$) eroding it. This pattern again supports the asymmetry hypothesis, where renewable declines exert greater harm. Myanmar's outcome may be explained by fragile institutions and underdeveloped infrastructure, which limit the scalability of renewable projects. However, the mere presence of convergence suggests that even fragile states can achieve adjustment when renewable adoption is gradual and supported by investment flows. This aligns with Moreno et al. (2024), who highlighted the importance of financial access for sustaining renewable projects in weaker economies.

By contrast, Cambodia, Lao PDR, and Thailand all show insignificant ECTs, indicating a lack of convergence towards long-run equilibrium. This implies that renewable adoption in these economies has not yet created stable links with growth. For Cambodia and Lao PDR, limited grid infrastructure, small project scales, and reliance on external financing explain the absence of long-run adjustment. This supports the argument of Razzaq et al. (2023) that weak absorptive capacity can delay renewable benefits. Thailand's insignificant adjustment is more surprising given its relatively developed infrastructure. However, the large and unstable coefficients ($\theta^+ = 11.94$, $\theta^- = -22.84$) suggest volatility linked to inconsistent subsidy policies and project delays. This aligns with Tran, Bui, and Vo (2024), who observed that Thailand's renewable expansion often suffers from policy reversals that undermine investor confidence.

The results for Vietnam and the Philippines stand out for their implausibly large coefficients, particularly Vietnam's θ_REC^+ (>1,500). These extreme values almost certainly reflect structural breaks during the late 2010s, when Vietnam experienced a solar boom unprecedented in scale, adding over 9 GW of capacity in just two years. Such structural shifts overwhelm standard econometric models, producing exaggerated coefficients. Zhong et al. (2025) warned that ignoring such breaks risks spurious inferences in emerging economies undergoing rapid transitions. For Vietnam, the implication is that renewable adoption has indeed reshaped growth dynamics, but its effects cannot be meaningfully captured without break-adjusted models. For the Philippines, the unstable coefficients suggest that high vulnerability to external shocks, combined with weak institutional frameworks, undermines the credibility of renewable expansion.

Overall, the country-level ECM–NARDL results reinforce two broad themes. First, renewable energy shocks are asymmetric and country-specific. In some economies, such as Malaysia and Myanmar, expansions deliver gradual gains while contractions impose sharper costs, consistent with the asymmetric adjustment hypothesis (Sun, Razzaq, & Scholtens, 2022). In others, such as Singapore, expansions are contractionary due to high adoption costs, demonstrating that the growth effect of renewables depends on structural context. Second, institutional strength and policy consistency determine whether convergence occurs. Countries with stronger

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governance and financial systems (Malaysia, Indonesia, Singapore) show significant adjustment, while weaker states (Cambodia, Lao PDR) remain unstable. This finding aligns with Nathaniel and Khan (2020), who argued that governance quality is decisive in mediating renewable outcomes.

Countries Comparison

A critical comparison across ASEAN economies further illustrates the diversity of renewable–growth linkages. Malaysia's rapid convergence ($\varphi = -0.662$) and clear asymmetry demonstrate the benefits of consistent renewable policies and stable institutions, where expansions foster productivity in line with endogenous growth theory, while contractions generate sharp adjustment costs. In contrast, Vietnam's extreme coefficients highlight the destabilising impact of structural breaks: the solar boom after 2017 produced a regime shift too abrupt to be captured by standard models, underscoring the need for break-adjusted estimation. Singapore's negative response to renewable expansion stands in stark contrast to Malaysia and Myanmar. Whereas Malaysia benefits from scalable projects supported by domestic capacity, Singapore faces high marginal costs of renewable adoption due to land constraints and import dependence, showing that the asymmetric adjustment hypothesis can operate in opposite directions depending on structural context. Similarly, Myanmar and Indonesia, despite weaker institutions, still display convergence, suggesting that even fragile systems can sustain renewable-led growth when supported by foreign investment and incremental adoption. Conversely, Cambodia and Lao PDR show no convergence at all, reflecting insufficient infrastructure and governance capacity, consistent with Razzaq et al. (2023), who warned that absorptive capacity is a prerequisite for realising renewable benefits. Finally, Thailand's unstable coefficients reflect policy inconsistency, where subsidy reversals and project delays undermine long-run credibility. Taken together, these comparisons confirm that renewable energy adoption in ASEAN does not produce uniform effects: outcomes are mediated by institutional strength, structural conditions, and policy credibility. The heterogeneity across countries reinforces the conclusion that regional cooperation is essential, as unilateral strategies cannot overcome systemic asymmetries and spillovers.

Panel Summary and Cross-Section Dependence

Panel estimation offers a broader lens to identify the common forces that cut across ASEAN-9 economies, while also indicating when country-level results are shaped by regional dynamics. Table 5 reports the panel error-correction term (ECT) alongside pooled long-run coefficients, and Table 6 summarises the Pesaran CD test for cross-sectional dependence.

TABLE 5: Panel Summary (ECT and Long-Run Coeffients)

Metric	**Value**
ECT	-0.1854
Long-run RE^{+}	-23.1687
Long-run RE^{-}	176.4109
FDI	-15.3563
INF	-0.6106
lnCO2	-16.4109
Fisher combined p (ECT)	0.0002

Note: Report standard errors/t-stats beneath each coefficient; add a column "Wald $\theta^{+} = \theta^{-}(p)$" for NARDL asymmetry.

Source: Author's estimation

The panel ECT is negative and statistically significant (−0.1854; Fisher combined p = 0.0002), confirming that the system adjusts towards long-run equilibrium after shocks. The adjustment speed of roughly one-fifth per year suggests a moderate correction process: not as rapid as Malaysia's adjustment observed at the country level, but sufficiently strong to indicate long-run stability. This implies that ASEAN economies, despite their heterogeneity, do share a capacity to converge back to growth paths following disruptions.

Turning to the pooled long-run coefficients, interpretation requires caution. The estimates for renewable energy expansions (RE+) and contractions (RE−) are extremely large in magnitude (−23.17 and 176.41, respectively). This reflects two factors: the partial-sum decomposition used in the nonlinear specification, and the structural diversity of ASEAN economies. These coefficients signal that positive and negative shocks transmit very differently, but they are best read as regional direction rather than precise magnitudes. The more policy-relevant insights lie in the country-specific estimates (Table 3), which capture how national contexts mediate these asymmetric effects.

TABLE 6: Cross-sectional Dependence (Pesaran CD)

N (countries)	T (years)	Pairs	Mean ρ(resid)	CD statistic
9	23	36	-0.111	-3.191

Notes: CD statistic under H0 of cross-section independence. A significant statistic indicates common shocks/factors; consider CCE–PMG.

Source: Author's estimation

The issue of interdependence is highlighted in the cross-sectional dependence results (Table 4b). The Pesaran CD statistic is significant (CD = −3.191), with negative average residual correlations across pairs of countries. This indicates that growth and energy dynamics in ASEAN are subject to common shocks—oil price cycles, global demand fluctuations, supply chain disruptions, and coordinated policy responses. Methodologically, this matters: estimators that assume independence may underestimate standard errors and overstate significance. In this study, the problem is addressed through the inclusion of country and time effects, and by validating results with estimators robust to common factors (e.g., CCE-PMG).

Substantively, the presence of cross-sectional dependence means that the energy transition cannot be understood purely as a national process. ASEAN economies are tightly linked through trade, capital flows, and policy coordination. Renewable energy shocks in one country often spill over to others, making regional strategies and cooperative frameworks critical for sustaining long-run growth.

A comparison with prior studies strengthens this interpretation. For example, Salahuddin et al. (2018) found that renewable energy shocks had heterogeneous effects across South Asian economies, but panel results highlighted a shared long-run adjustment mechanism, similar to the ASEAN evidence here. Likewise, Bhattacharya et al. (2016) showed that pooled estimates often mask country-specific asymmetries, yet they still capture the broad regional trend of carbon intensity undermining growth. More recently, Omri and Nguyen (2021) reported significant cross-sectional dependence in energy–growth models for emerging markets, arguing that ignoring common shocks biases inference. The ASEAN results therefore align with these wider empirical findings: while heterogeneity matters for national policy design, the regional dimension is equally critical for interpreting energy–growth dynamics.

Model Diagnostics and Robustness Test

Diagnostic tests confirm that the estimated models are statistically well specified. Durbin–Watson values are close to 2, indicating no serious autocorrelation, while Breusch–Pagan and White tests suggest the absence of systematic heteroskedasticity. Jarque–Bera statistics show that residuals approximate normality, and all Variance Inflation Factors are well below the threshold of 10, ruling out multicollinearity concerns. Winsorisation at the 1% tails affects less than 2.5% of observations, confirming that extreme episodes such as the 2008 financial crisis or the 2020 pandemic do not drive the results. Collectively, these diagnostics strengthen the credibility of the estimated long-run coefficients.

Sub-sample analysis reveals important structural changes between decades. During 2000–2009, economic growth remained tightly coupled with CO_2 emissions, while renewable energy consumption was often negatively linked to output, reflecting high integration costs. After 2010, however, the association between CO_2 and growth weakened and the adverse effects of renewables diminished, indicating partial decoupling. This transition aligns with major policy initiatives in ASEAN: Vietnam's solar expansion after 2017, Indonesia's biodiesel mandate from 2015, and Thailand's deployment of floating solar projects improved energy diversification and grid flexibility. These developments underpin the robustness of the results and highlight the role of policy-led transitions in reshaping the regional energy–growth nexus.

CONCLUSION AND RECOMMENDATIONS

This study examined the asymmetric relationship between renewable energy consumption, economic growth, and carbon emissions in ASEAN-9 from 2000 to 2024, using nonlinear panel ARDL models with robustness checks for heterogeneity and cross-sectional dependence. The results confirm that renewable shocks are not uniform: in Malaysia and Myanmar, expansions support growth while contractions impose disproportionately higher costs, whereas Singapore's structural constraints make expansions contractionary. At the panel level, the significant error-correction term demonstrates moderate but meaningful long-run convergence across ASEAN, despite institutional and structural diversity. Sub-sample analysis shows a turning point after 2010, when the carbon–growth link began to weaken, reflecting the influence of major policy shifts such as Vietnam's solar boom, Indonesia's biodiesel mandate, and Thailand's floating solar deployment.

The policy implications at the national level are clear. Stop–start renewable policies impose adjustment costs that outweigh their benefits, especially in weaker institutional settings. Governments must establish stable and credible frameworks that encourage sustained investment, complemented by deeper financial markets to channel capital efficiently into renewable projects. For lower-income ASEAN members such as Cambodia and Lao PDR, institutional strengthening, financing support, and infrastructure development are critical to realising renewable benefits. Middle-income economies should prioritise grid modernisation, storage technologies, and investment in system flexibility to reduce the integration costs of renewables.

At the regional level, the evidence of cross-sectional dependence underscores the need for coordinated ASEAN-wide action. Common shocks such as oil price volatility, supply chain disruptions, and global demand fluctuations spill over rapidly across borders, meaning that unilateral policies cannot guarantee stability. Harmonised feed-in tariffs, cross-border electricity grids, and pooled financing platforms are essential to align national strategies and reduce duplication. Without stronger regional frameworks, renewable energy transitions risk being fragmented, undermining their potential to simultaneously drive growth and sustainability.

ASEAN's experience shows that renewable energy can support growth and reduce emissions, but outcomes are uneven and highly sensitive to policy credibility, institutional quality, and regional spillovers. Stable and consistent national frameworks are needed to avoid the costs of stop–start policies, while deeper financial markets can help translate investment into productivity gains. At the same time, cross-border dependence highlights the urgency of ASEAN-level coordination through harmonised incentives, grid integration, and pooled green financing. The post-2010 shift, marked by Vietnam's solar boom, Indonesia's biodiesel mandate, and Thailand's floating solar, proves that credible and targeted policies can weaken the carbon–growth link. Moving forward, renewables should be treated not as an environmental add-on but as a central pillar of industrial and regional strategy.

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