CLIMATE RISKS AND CLEAN COOKING ENERGY FOR SUSTAINABLE FUTURES: EMPIRICAL EVIDENCE FROM SOUTHEAST ASIA

WEI, R.[1*] – ADELEKE, O. K.[2,3] – OKOGOR, K. C.[2,4] – OSABOHIEN, R.[2,5]

[1]*Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China*

[2]*Department of Economics, Redeemer's University, Ede, Nigeria*

[3]*DEPECOS Institutions and Development Research Centre (DIaDeRC), Ota, Nigeria*

[4]*Department of Economics Delta State University, Abraka, Nigeria*

[5]*Institute of Energy Policy and Research (IEPRe), Universiti Tenaga Nasional (UNITEN), Kajang, Malaysia*

**Corresponding author*
e-mail: weiruan_smu@yeah.net

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Abstract. This study examines the complex interplay between climate risks, clean cooking energy adoption, and sustainable development across ten Southeast Asian (ASEAN) countries, Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam over the period 2013 to 2022. Drawing on panel data from the World Bank (WDI), European Commission's DRMKC, UN-DESA, IMF-DOTS, and the World Economic Outlook (WEO), the analysis focuses on two central research questions: (1) What is the impact of climatic risk indicators on sustainable development? and (2) What is the effect of clean energy adoption for cooking on sustainability outcomes? Sustainable development is proxied by Adjusted Net Savings (ANS), while climate risk is captured through indices measuring hazard and exposure, INFORM risk, lack of coping capacity, and vulnerability. Clean energy is measured by the share of the population with access to clean fuels and technologies for cooking. The study applies a three-stage econometric strategy: Pooled Ordinary Least Squares (Pooled OLS) as a benchmark, Fixed Effects (FE) to account for unobserved country heterogeneity, and the Generalized Method of Moments (GMM) to address endogeneity concerns. The findings reveal that greenhouse gas emissions consistently reduce ANS across all models, indicating the economic cost of environmental degradation. Clean cooking energy shows a strong positive impact in OLS but exhibits weaker or insignificant effects under FE and GMM, suggesting delayed or indirect channels of influence. Climatic risk indicators display both intuitive and counter-intuitive effects, reflecting varying degrees of resilience-building and external support. Policy implications stress the need for investment in climate-resilient infrastructure, the scaling of clean cooking technologies, and regional strategies for low-carbon trade.
Keywords: *climatic risk, clean energy adoption, environmental sustainability, sustainable development*

Introduction

The Association of Southeast Asian Nations (ASEAN) region is increasingly facing challenges related to climatic risks, prompting the need for sustainable development strategies that focus on clean energy adoption (Mohamed et al., 2024; Osabohien et al., 2024). Climate change poses a significant threat to economic stability and environmental sustainability (Degbedji et al., 2024), making it crucial for ASEAN countries to prioritize clean energy solutions to mitigate the impacts of global warming.

In recent years, there has been a growing recognition of the importance of transitioning to renewable energy sources and reducing carbon emissions to address climate change

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concerns (Degbedji et al., 2024; Li et al., 2023; Mohamed et al., 2024; Sahan et al., 2024). Clean energy adoption not only helps reduce greenhouse gas emissions but also promotes energy security, economic growth, and job creation within the ASEAN region. However, the adoption of clean energy technologies and sustainable development practices in ASEAN countries face various challenges, including policy and regulatory barriers, financial constraints, and technological limitations. Overcoming these challenges requires a comprehensive understanding of the economic implications of climate change, the benefits of clean energy adoption, and the potential pathways to sustainable development in the region.

This study aims to empirically assess the effects of climatic risks and clean cooking energy adoption on sustainable development in Southeast Asia. Sustainable development is proxied by adjusted net savings, while climatic risk is captured using multi-dimensional indicators such as climate-driven hazards and exposure, the INFORM risk index, coping capacity, and vulnerability. Clean cooking energy and greenhouse gas emissions serve as core explanatory variables, alongside control variables including economic growth, urbanization, and trade in low-carbon products. By employing panel data econometric techniques, this study seeks to uncover the extent to which climate resilience and energy transitions shape sustainable development trajectories across Southeast Asian countries, thereby contributing to both academic literature and regional policy discourse on climate-compatible development. promoting sustainable development and resilience to climatic risks. The research of the study includes:

RQ1: *what is the impact of climatic risk indicators on sustainable development?*

The research question seeks to understand how specific indicators of climatic risk, namely Climate-driven Hazard & Exposure, Climate-driven INFORM Risk Indicator, Lack of coping capacity, and Vulnerability, influence sustainable development outcomes. By examining the relationship between these indicators and sustainable development, researcher aims uncover the ways in which climate-related hazards and vulnerabilities affect the ability of communities, regions, and systems to achieve long-term social, economic, and environmental goals. In summary, by investigating the impact of these climatic risk indicators on sustainable development, researchers can generate evidence-based insights that inform policy decisions, resource allocation, and community engagement strategies aimed at building resilience, reducing vulnerabilities, and advancing sustainable development goals in the face of climate change.

RQ2: *What is the impact of clean cooking energy adoption on sustainable development?*

The research question focuses on investigating the relationship between the adoption of clean energy, specifically measured by access to clean fuels and technologies for cooking as a percentage of the population, and its impact on sustainable development outcomes, which are measured by adjusted next saving. This indicator reflects the extent to which households have transitioned from traditional cooking methods using solid fuels to cleaner alternatives such as liquefied petroleum gas (LPG), biogas, electric stoves, or other clean cooking solutions. By measuring the proportion of the population with access to clean cooking technologies, researcher can assess the level of clean energy adoption within a given context and evaluate progress towards achieving universal access to clean energy services.

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Literature review

Some stylized facts

Global progress towards universal access to clean cooking technologies has been noteworthy in recent decades. However, despite a steady reduction in the number of people lacking such access, significant regional disparities persist. Nowhere is this divergence more pronounced than in Africa, particularly Sub-Saharan Africa where the number of individuals without access continues to rise by approximately 20 million each year. This annual increase outweighs the rate of progress and presents a serious challenge for the nearly one billion people already exposed to the detrimental health and environmental effects of polluting cooking methods (FAO, 2023). Without urgent corrective action, the growing access gap in Sub-Saharan Africa could reverse the current upward global trend in clean energy adoption.

The implications of this trend are deeply concerning. Projections by Dagnachew et al. (2020) suggest that, absent significant policy reform, as many as 820 million people in Sub-Saharan Africa may still be reliant on traditional biomass cookstoves by 2030. Exacerbating the situation, recent shocks such as the COVID-19 pandemic and intensified global climate mitigation efforts are predicted to leave an additional 470 million and 200 million people, respectively, unable to afford clean cooking services (Pachauri et al., 2021). These findings underscore the necessity for a multidimensional policy approach that includes large-scale public and private investments, user-centered technological designs, and targeted regional interventions (Zhang, 2021). To meet the 2030 target for universal access to clean cooking, investment in cookstove technologies must increase fourfold from current levels (Dagnachew et al., 2020). This would not only deliver significant social and health dividends but also support environmental and economic goals, particularly in under-served regions.

A broader view of global progress is captured in *Figure 1,* which illustrates access to clean fuels and cooking technologies by continent—Africa, Europe, South-East Asia, and the Western Pacific as well as globally, comparing data from 1990 and 2021. This indicator serves as a key proxy for household energy security, environmental protection, and public health. The encouraging global trend reflects a substantial increase in access between the two benchmark years, suggesting considerable progress towards Sustainable Development Goal 7 (SDG 7), which aims to secure universal access to affordable, reliable, and modern energy services.

Regionally, trends vary markedly. Africa, though starting from a low base of 11.9% in 1990, recorded an increase to 21% by 2021. While this improvement is notable, the continent still trails significantly behind others, revealing a persistent reliance on traditional biomass and polluting fuels. This continued dependency not only exacerbates indoor air pollution but also imposes a heavy time and health burden, especially on women and children. In stark contrast, Europe has maintained near-universal access levels, rising modestly from 92.8% in 1990 to 93% in 2021. This stability reflects the integration of clean cooking solutions into established energy infrastructure, bolstered by mature economies and effective policy regimes.

The most remarkable advancements have been observed in Asia. South-East Asia experienced a surge in access from just 10.4% in 1990 to an impressive 67.5% in 2021, driven by targeted government interventions, increasing affordability of cleaner alternatives like LPG and electricity, and overall economic growth. The Western Pacific region also saw substantial gains, climbing from 39.6% to 82.6% over the same period.

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These figures suggest that policy coherence and investment in clean energy infrastructure have played vital roles in these successes.

Globally, access to clean cooking fuels rose from 44.2% in 1990 to 71.1% in 2021. This progress has been largely propelled by improvements in Asian regions. Yet, it remains sobering that nearly 30% of the global population still lacked access as of 2021. This gap reflects not only developmental disparities but also the pressing need for scalable and inclusive solutions. Bridging this deficit will require continued investment in infrastructure, policy support for clean energy innovation, and public education to encourage behavioral change. These efforts are essential not only for improving health outcomes and reducing environmental degradation but also for promoting gender equity by reducing the unpaid labor associated with fuel gathering.

Further substantiating these regional differences, FAO (2023) reports a steady decline in the number of people lacking access to clean cooking technologies in Eastern and South-Eastern Asia since 2000, and in Central and Southern Asia since 2010. However, Sub-Saharan Africa presents a stark contrast: the number of people without access has more than doubled since 1990. The primary driver of this trend is rapid population growth outpacing improvements in access. Since 2000, the region's access deficit has expanded by roughly 60%, with approximately 900 million people affected by 2021. Projections indicate that, in the absence of decisive policy measures, the number of people lacking access could climb to 1.1 billion by 2030, threatening to entrench energy poverty in the region for decades to come (FAO, 2023).

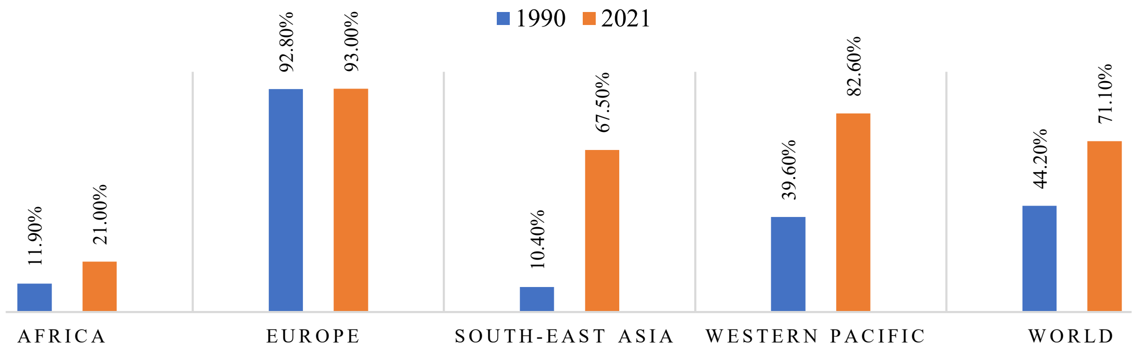

Figure 1. *Access to clean fuels and technologies for cooking (% of population). Source: Authors computation using Our World in Data*

Theoretical and empirical review

Studies have shown that ASEAN is susceptible to rising sea levels, increased frequency and intensity of natural disasters such as typhoons, floods, and droughts, and shifting agricultural patterns (Yusuf and Francisco, 2009). Recent studies expand the understanding of climate impacts and mitigation pathways. Zhu et al. (2025a) identify tropical convection patterns and monthly anomalies influencing Eurasian climate dynamics, emphasizing atmospheric teleconnections. Ganesh and Pragasan (2022) show nitrogen addition enhance Eucalyptus growth and carbon sequestration under varied CO_2 conditions.

Khalaf and Rustum (2024) assess projected extreme climate change on water reservoir operations, highlighting infrastructure vulnerabilities. Meanwhile, Zhu et al. (2025b) employ physics-based methods for climate anomaly forecasting. These studies reinforce

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the need for integrative, predictive, and ecosystem-based approaches to climate change mitigation, complementing energy-focused strategies in China. These climatic changes pose significant risks to food security, livelihoods, and economic stability.

The varying levels of development and adaptive capacities among ASEAN countries influence their vulnerability to climate change, with research indicating that poorer nations within the bloc face greater risks and possess fewer resources for effective adaptation (ADB, 2017).

ASEAN has substantial potential for renewable energy development, particularly in solar, wind, hydro, and biomass (IRENA, 2018). However, studies highlight that while progress has been made in developing supportive policies, inconsistencies in implementation remain a key challenge (UNESCAP, 2019). Regional cooperation and harmonization of energy policies are therefore essential to unlock the full potential of renewable resources in promoting sustainable development.

Transitioning to clean energy offers several economic and environmental benefits, including job creation, improved energy security, and reduced greenhouse gas emissions. Clean energy investments have been shown to drive sustainable economic growth, particularly in developing regions like ASEAN (IRENA, 2016). In alignment with the United Nations Sustainable Development Goals, especially SDG 7 and SDG 13, the literature emphasizes the need for integrated strategies that address the interlinkages between energy access, climate resilience, and sustainability (UNDP, 2020).

Despite these advancements, ASEAN continues to grapple with persistent challenges such as poverty, inequality, and environmental degradation. Evidence suggests that promoting clean energy technologies especially for household uses such as cooking and building resilience to climate-related risks can significantly support the region's sustainable development agenda (ASEAN Centre for Energy, 2021). The complex interplay between climate risks, clean cooking energy, and sustainability requires robust policies, coordinated regional efforts, and targeted investments to ensure inclusive energy access.

Ecosystem vulnerability and renewable energy assessment by Dai et al. (2022) further supports this position, noting that clean energy, particularly in household use, is effective in moderating temperature and reducing CO_2 emissions. Clean cooking energy, being carbon-neutral, contributes meaningfully to ecosystem stability and reduced health risks from indoor air pollution. However, several countries still encounter social and political resistance in scaling up renewable energy use, especially in low-income settings. Studies (Li et al., 2024; Matthew et al., 2020; Onabote et al., 2021; Yin et al., 2022; Zheng et al., 2023) consistently emphasize the importance of clean energy programs tailored to the energy sector of low-income countries. These programs, when well-targeted, reduce ecosystem vulnerability by lowering reliance on fossil fuels and enhancing households' resilience to climate-related shocks. The macroeconomic literature supports the view that clean energy adoption can mitigate climate risks through both environmental and health-related channels.

Furthermore, the literature underscores a nonlinear relationship between clean energy and environmental degradation. Increasing clean cooking energy adoption enhances a population's ability to cope with climatic variability, reducing the burden on health systems and food security. This highlights the need for optimized energy transitions that include equitable distribution, cost-effective technologies, and policies that prioritize clean cooking infrastructure in vulnerable communities.

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Methodology

Variable description

The research utilized data covering the period 2013-2022 obtained from various sources, including the European Commission, DRMKC (Disaster Risk Management Knowledge Centre), UN-DESA (United Nations Department of Economic and Social Affairs), IMF-DOTS (International Monetary Fund Direction of Trade Statistics), and WEO (World Economic Outlook), as detailed in *Table 1*. The data pertained to ten ASEAN countries: Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam. The study employed statistical techniques such as Pooled Ordinary Least Squares (Pooled OLS), fixed effects, and the Generalized Method of Moments (GMM). The model is represented by *Equation 1*.

$$lnSD_{it} = a_0 + a_1 lnCRISK'_{it} + a_2 lnCEN_{it} + a_3 lnZ'_{it} + e \qquad \text{(Eq.1)}$$

where $lnSD_{it}$ is the natural logarithm of sustainable development (measured by adjusted net savings) Where a_0 captures the constant term, $a_1, a_2, and\ a_3$ represent the coefficients of the independent and control variables, e is the error term, i represents the countries of study and t represents the study period. Furthermore, $CRISK'$ stands for the covariate of climatic risks and its coping strategies which include climate-driven Hazard and Exposure (index), climate-driven INFORM risk indicator (index), lack of coping capacity and vulnerability.

Furthermore, CEN_{it} is clean energy measured by access to clean fuels and technologies for cooking (% of population)) for country i at time t. On the other hand, z' is the covariate of control variables which include economic growth measured by GDP growth (annual %), Urbanization measured by urban population growth (annual %) and trade in low-carbon products (USD)(% GDP) and total trade in low carbon technology products (USD).

Table 1. *Variables, measurement and sources*

Variables	Measurement	Source
Sustainable development	Adjusted net savings, excluding particulate emission damage (% of GNI)	WDI
CDRHE	Climate-driven Hazard & Exposure (Index)	DRMKC
CDIRI indicator	Climate-driven INFORM Risk (Index)	DRMKC
Locs	Lack of coping capacity	DRMKC
Vul	Vulnerability	DRMKC
GDP growth	GDP growth (annual %)	WDI
Urbanization	Urban population growth (annual %)	WDI
Clean energy	Access to clean fuels and technologies for cooking (% of population)	WDI
LCTP8	Total trade in low carbon technology products	UN-DESA, IMF-DOTS, WEO
LCTP9	Total trade in low carbon technology products as percent of GDP	

Means EC European Commission, DRMKC means Disaster Risk Management Knowledge Centre; UN-DESA means United Nations Department of Economic and Social Affairs (DESA). IMF-DOTS means International Monetary Direction of Trade Statistics (DOTS); and WEO means World Economic Outlook (WEO)

Model specification and estimation strategy

To examine the impact of climatic risk and clean energy adoption for cooking on sustainable development in Southeast Asia, this study employed a multi-step econometric estimation approach, comprising Pooled Ordinary Least Squares (Pooled OLS), Fixed

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Effects (FE), and the Generalized Method of Moments (GMM). The empirical model guiding the estimation is presented in *Equation 1*.

The Pooled OLS technique was initially used as a benchmark model. Its selection is justified on the grounds that it provides a simple and efficient starting point for estimating panel data models when the assumption of homogeneity across cross-sectional units is considered plausible. Specifically, Pooled OLS combines time-series and cross-sectional observations, treating the dataset as a single cross-section without controlling for individual country-specific effects. Although limited in controlling for unobserved heterogeneity, it offers a useful reference point for comparing with more advanced estimators. It also aids in assessing the overall direction and magnitude of relationships in the absence of fixed or random effects. However, recognizing that the assumption of cross-sectional homogeneity is often unrealistic in panel settings especially across diverse ASEAN countries, this study subsequently employed the Fixed Effects model. The FE estimator controls for time-invariant, country-specific characteristics that may bias the estimates in Pooled OLS, thereby improving reliability when heterogeneity across countries is non-negligible.

In addition to heterogeneity, one of the key concerns in this study is the possibility of endogeneity arising from reverse causality (e.g., higher sustainable development may lead to increased investment in clean cooking energy), measurement errors, or omitted variables. To address these issues and improve the robustness of the estimates, this study further employed the Generalized Method of Moments (GMM) estimator. GMM is particularly effective in handling endogeneity by using internal instruments typically lagged levels or differences of the endogenous variables and is appropriate for datasets with a short time dimension (T) and a relatively larger cross-sectional dimension (N), as is the case in this study.

Specifically, the study applies the Arellano-Bond difference GMM estimator, which not only accounts for endogeneity but also corrects for potential autocorrelation and heteroskedasticity. By instrumenting potentially endogenous variables with their appropriate lags, GMM ensures consistent and efficient parameter estimation, making it highly suitable for dynamic panel data models involving variables like clean energy adoption and sustainable development that may influence each other over time.

Results and discussion

Summary statistics

This section presents a detailed summary of the key variables utilized in the empirical analysis, based on panel data drawn from Southeast Asian countries. The descriptive statistics offer insights into the central tendencies, dispersion, and distributional characteristics of the variables, thereby enhancing understanding of the heterogeneity present across time and entities in the dataset. The result for the summary or descriptive statistics is presented in *Table 2*.

Adjusted Net Savings (as a proxy for sustainable development) exhibits a mean value of 45.07, with a standard deviation of 28.15, indicating substantial variation across countries and time periods. The minimum value of 1 and maximum of 94 underscore the significant disparity in savings performance and the extent of intertemporal and cross-country differences in sustainability-related fiscal capacity.

GDP Growth displays a mean of 3.97% and a standard deviation of 4.05%, reflecting a generally positive but volatile economic performance in the region. The observed values

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span a wide interval, ranging from a contraction of -12.02% to a maximum growth of 8.88%, suggesting substantial fluctuations in macroeconomic conditions, likely attributable to varying levels of resilience, policy responses, and exposure to external shocks. Urban Population Growth has an average value of 2.15%, with a standard deviation of 0.99%, indicating moderate variability in the pace of urbanization. Notably, the data ranges from -4.17%, indicating urban population decline in some cases, to 3.40%, reflecting periods of urban expansion. These trends highlight the dynamic and often uneven urbanization patterns within the region.

Access to Clean Energy for Cooking, the central variable of interest, reveals a mean of 63.53% with a notably high standard deviation of 33.57%, pointing to significant heterogeneity in clean energy access across the sample. The spread between the minimum value of 4.3% and maximum of 100% indicates that while some countries have achieved full coverage, others still face severe energy access deficits. Climate-driven Hazard and Exposure presents a mean of 5.51 and a standard deviation of 2.49, suggesting moderate average exposure to climate-induced hazards, with considerable variation across countries. The values range from 0.1 to 8.2, highlighting stark contrasts in climatic risk intensity and exposure levels within the ASEAN region.

The Climate-driven INFORM Risk Indicator records a mean of 4.16 and a standard deviation of 1.76. The values range from 0.3 to 6.8, reflecting varying degrees of composite climate risk across observations. The dispersion points to notable differences in national risk profiles and adaptive capacity. Lack of Coping Capacity exhibits a mean of 4.34, with a standard deviation of 1.56, suggesting moderate deficits in institutional, economic, and infrastructural readiness to manage climate-related shocks. The range from 1.0 to 7.3 illustrates the unequal distribution of resilience and response capacity across the region. Vulnerability, another core dimension of climate risk, records a mean of 3.20 and a standard deviation of 1.61. The minimum value of 0.3 and maximum of 6.4 underscore significant disparities in susceptibility to climate-related harms, often reflective of underlying socioeconomic and environmental conditions.

Trade in Low-Carbon Products (USD) reveals a mean value of USD 1.15×10^{10}, with a remarkably high standard deviation of USD 1.22×10^{10}, indicating extreme variability in trade volumes across countries. The observed values range from USD 8.70×10^{7} to USD 4.47×10^{10}, suggesting large structural differences in export and import capacity related to low-carbon technologies and products.

When expressed as a percentage of GDP, Trade in Low-Carbon Products records a mean of 3.65% and a standard deviation of 3.12%, further revealing significant variation in the economic importance of low-carbon trade. The values range from 0.50% to 10.87%, highlighting a wide spectrum of integration into the green economy among the countries studied. Overall, the descriptive statistics highlight substantial heterogeneity across the ASEAN panel, both in terms of clean energy adoption for cooking and climate risk indicators. This variability justifies the adoption of panel data econometric techniques that account for unobserved heterogeneity and potential endogeneity in subsequent empirical analysis (*Table 2*).

Empirical results: pooled OLS estimations

This section presents the results from the Pooled Ordinary Least Squares (Pooled OLS) regressions, which investigate the determinants of sustainable development across ASEAN countries. Sustainable development is proxied by Adjusted Net Savings, a widely recognized indicator of long-term economic and environmental performance. The

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result for the pooled OLS is presented in table 3. Six regression models are reported (as shown in *Table 3*), progressively incorporating explanatory variables to assess their individual and combined effects on sustainable development outcomes.

Table 2. *Summary statistics*

Variable	Mean	Std. dev.	Min	Max
Adjusted net savings	45.07	28.15156	1	94
GDP growth	3.967327	4.053693	-12.01637	8.882354
Urban population	2.149738	0.9931027	-4.170336	3.398847
Access to clean energy	63.53	33.56535	4.3	100
Climate-driven hazard & exposure	5.51	2.488945	0.1	8.2
Climate-driven INFORM risk indicator	4.157	1.755353	0.3	6.8
Lack of coping capacity	4.341	1.563607	1	7.3
Vulnerability	3.203	1.605449	0.3	6.4
Trade in low-carbon products (USD)	1.15E + 10	1.22E + 10	8.70E + 07	4.47E + 10
Trade in low-carbon products (% GDP)	3.646806	3.12253	0.496195	10.87438

Source: Authors' computation

Across all specifications, the constant term is positive and statistically significant at the 1% level, indicating a baseline level of sustainable development in the absence of explanatory variables. The robustness and consistency of this finding across models reinforce the reliability of the specification framework. Economic Output (proxied by the logarithm of GDP) emerges as a consistent and statistically significant positive determinant of sustainable development across all models in which it is included. The estimated coefficients range from 0.2649 to 0.3059 and are statistically significant at the 5% or 1% levels. This suggests that higher levels of economic activity are associated with increased savings and sustainable investment capacity, supporting the hypothesis that economic growth enables governments and households to allocate more resources towards sustainability-enhancing initiatives.

Urban Population Growth is found to have a negative and statistically significant association with sustainable development in all model specifications. The coefficients, ranging from -0.3302 to -0.4983, are uniformly significant at the 1% level. This finding implies that urban expansion, in its current form, may be exerting pressure on natural resources, infrastructure, and public services, thereby diminishing net savings and impeding progress towards sustainable development. The result highlights the critical need for integrated urban planning that aligns population growth with sustainable infrastructure and energy provision.

Access to Clean Energy and Technology for Cooking demonstrates a strong and statistically significant positive relationship with sustainable development across all models. Coefficients fall within the range of 0.8691 to 1.0044 and are consistently significant at the 1% level. This result is in line with Dai et al. (2022) and confirms the hypothesis that improved access to clean cooking energy, by reducing health risks, environmental degradation, and inefficient energy use, substantially enhances long-term sustainability outcomes. Climate-Driven Hazard and Exposure becomes significant upon introduction in Model 2, with a positive coefficient of 0.1300 (significant at the 5% level).

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Although counter-intuitive, this result may indicate that regions more exposed to climate hazards tend to receive greater resilience-oriented investments or development aid, which may ultimately increase adjusted net savings. It also suggests a possible policy feedback loop wherein greater risk exposure prompts proactive sustainability strategies. Similarly, the Climate-Driven INFORM Risk Indicator in Model 3 exhibits a positive and highly significant relationship with sustainable development (coefficient = 0.2949; significant at 1%). This reinforces the earlier finding and suggests that perceived or actual climate risk may be associated with higher levels of adaptation and mitigation investment, potentially through both domestic initiatives and international support mechanisms.

The Lack of Coping Capacity variable, introduced in Model 4, also shows a statistically significant and positive association with sustainable development (coefficient = 0.5226; 1% significance level). While this appears paradoxical, it may reflect targeted interventions in areas with low resilience, leading to increased resource flows for sustainable development efforts.

Vulnerability, added in Model 5, retains this trend, showing a positive and significant effect (coefficient = 0.3725; significant at 5%). As with other risk-related indicators, this may point to the mobilization of support and structural responses to vulnerability, which ultimately enhance sustainability outcomes.

Model 6 introduces two trade-related variables. Total Trade in Low-Carbon Technology Products (in logarithmic form) shows a negative and statistically significant relationship with sustainable development (coefficient = -1.7200; significant at 5%). This suggests that, in the short term, the acquisition of such technologies may impose fiscal burdens that reduce net savings, possibly due to high import costs or trade imbalances. Conversely, the proportion of low-carbon technology trade as a share of GDP is negative but statistically insignificant, suggesting that the relative size of such trade may be less important than its absolute economic weight. Regarding model performance, the R-squared values across specifications range from 0.4203 to 0.4406, indicating that the explanatory variables account for approximately 42–44% of the variation in sustainable development. The F-statistics for all models are statistically significant at the 1% level, confirming the joint significance of the included regressors and the overall validity of the model specifications.

The findings reveal several consistent and noteworthy patterns. Economic growth and access to clean cooking energy emerge as robust and positive drivers of sustainable development in ASEAN countries. These results affirm the importance of promoting clean household energy solutions not only for environmental and health reasons but also for their contribution to broader developmental outcomes.

Conversely, urbanization poses a persistent challenge to sustainability, suggesting that unplanned or poorly managed urban expansion may undermine environmental and fiscal stability. This underlines the need for targeted policies that support sustainable urban infrastructure, housing, and service delivery.

Perhaps most intriguing are the positive associations between sustainable development and indicators of climatic risk and coping limitations. These results, while initially counter-intuitive, may reflect indirect benefits derived from resilience-building responses, aid inflows, or increased policy attention to vulnerable regions. Such dynamics merit further investigation, particularly through qualitative case studies or dynamic modelling. Finally, the negative relationship between trade in low-carbon technologies and sustainable development highlights potential short-term trade-offs involved in clean energy transitions. This suggests that without accompanying policies such as technology transfer, local manufacturing, or concessional financing, reliance on imported clean technologies may constrain domestic savings and delay the net gains from sustainable investments (*Table 3*).

Table 3. *Pooled OLS*

	Dependent variable: adjusted net savings					
Variable	**1**	**2**	**3**	**4**	**5**	**6**
Cons	3.3054*** (0.000)	3.1725*** (0.000)	2.2974*** (0.001)	3.2668*** (0.000)	2.5612*** (0.000)	3.0154*** (0.000)
lgdpg	0.2959* (0.081)	0.2928* (0.090)	0.3059* (0.086)	0.2649* (0.095)	0.3024* (0.083)	0.2977* (0.079)
Lupop	-0.4559** (0.048)	-0.4983** (0.028)	-0.4858** (0.023)	-0.4702** (0.024)	-0.4037* (0.066)	-0.3302 (0.110)
Acftfc	0.8691*** (0.000)	0.9408*** (0.001)	0.9765*** 0.000)	1.0044*** (0.002)	0.9100*** (0.001)	0.8698*** (0.000)
Lcdrhe	0.1300** (0.010)					
Cdiri		0.2949*** (0.008)				
Locs			0.5226*** (0.000)			
Vul				0.3725** (0.034)		
lctp8					-1.7200* (0.052)	
lctp9						-0.0321 (0.160)
R-squared	0.4203	0.4319	0.4361	0.4406	0.4291	0.4140
Prob > F	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***

***, **, * indicates statistical significance at 1%, 5% and 10% respectively
Source: Authors' computation

Fixed effect regression results (Models 7–12)

The regression results for the fixed effects from Models 7 through 12 (presented in *Table 4*) explore alternative specifications for identifying the determinants of sustainable development, proxied by Adjusted Net Savings, across ASEAN countries. Each model incorporates different combinations of explanatory variables to test the robustness and sensitivity of the empirical relationships.

The overall fit of the models varies considerably. R-squared values range from 0.2092 in Model 11 to 0.5393 in Model 10, indicating that the models account for approximately 21% to 54% of the variation in Adjusted Net Savings. Model 10 presents the best explanatory power among the specifications. Despite this variability, all models are jointly statistically significant at the 1% level, as indicated by Prob > F values of 0.0000. This confirms that at least one explanatory variable in each model significantly influences the dependent variable.

Across all specifications, the constant term remains positive and statistically significant, suggesting a baseline level of adjusted net savings irrespective of other included covariates.

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The logarithm of GDP shows inconsistent effects across the models. In Models 7, 8, 10, 11, and 12, the coefficient is not statistically significant, and the sign alternates. Only in Model 9 does it emerge as positive and significant at the 1% level. This variability suggests that the effect of GDP on sustainable development may be conditional on the presence of other explanatory variables, reflecting either indirect pathways or potential multicollinearity. The lack of a consistently significant effect may also suggest that economic growth alone does not sufficiently capture the structural or institutional drivers of sustainability.

The influence of urbanization, as captured by the log of urban population, also exhibits variability. In Model 7, it is negatively associated with adjusted net savings, albeit weakly (significant at 10%). However, in Models 8 to 10, the relationship becomes positive and statistically significant, suggesting that under certain conditions, urbanization may contribute to sustainable development—possibly through economies of scale, infrastructure efficiency, or innovation diffusion. In contrast, the negative and insignificant coefficients in Models 11 and 12 indicate that the effect of urbanization is highly sensitive to model specification and may be context-dependent.

Access to clean energy and technology for cooking presents a similarly mixed pattern. It is positive and significant in Models 7, 8, and 12, but notably negative and highly significant in Model 9. This inconsistency raises concerns about potential omitted variable bias or multicollinearity. Given the well-established benefits of clean energy for health, environmental quality, and productivity, the negative sign in Model 9 is likely an artefact of model specification and warrants further exploration in robustness tests or alternative estimators.

The variable Ltghge consistently exhibits a negative and highly statistically significant relationship with Adjusted Net Savings In Models 7, 8, 10, 11, and 12, with coefficient estimates ranging from -2.6373 to -113.646, all significant at the 1% level. These findings provide robust empirical confirmation of the adverse effect of environmental degradation manifested through increased greenhouse gas emissions on long-term sustainability. The negative relationship aligns with theoretical expectations and sustainability principles, suggesting that higher emissions diminish a nation's capacity to accumulate wealth sustainably. This association can be attributed to the direct and indirect economic costs associated with emissions, including the impacts of climate change, increased public health burdens, resource depletion, and the depreciation of natural capital. These effects undermine long-term productivity and impose fiscal and environmental liabilities, thereby eroding net savings. The consistency and statistical strength of these findings across multiple models underscore the systemic nature of this relationship.

Notably, Model 9 diverges from this pattern, reporting a positive and statistically significant coefficient for Ltghge (3.6200***). While counter-intuitive, this result may reflect specific transitional dynamics in certain economies. In rapidly industrializing or resource-dependent countries, higher emissions may temporarily coincide with increased physical capital accumulation and gross savings, particularly in the context of fossil-fuel-driven growth. For instance, emissions-intensive sectors may generate substantial short-term revenues, which bolster national savings figures before accounting for long-term environmental costs. Alternatively, the result may reflect model-specific issues such as omitted variable bias, unobserved heterogeneity, or the exclusion of relevant environmental or institutional controls, warranting further empirical scrutiny.

Although Model 9 suggests a positive short-term association between emissions and savings, this should not be interpreted as a viable development path. The long-run

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implications of emissions-driven growth are unsustainable, as the environmental costs eventually surpass short-term economic benefits. Policymakers should thus be cautious in interpreting such isolated results and focus on structural reforms that internalize environmental externalities into national accounting systems. Among the climate-related variables, climate-driven hazard and exposure is included only in Model 7 and shows a strong positive association with adjusted net savings. This may suggest that countries exposed to greater climate risks invest more heavily in resilience and adaptation, potentially enhancing long-term sustainability outcomes.

In contrast, the climate-driven INFORM risk indicator in Model 8 is negatively associated with the dependent variable, which aligns more intuitively with the notion that higher perceived or real risk suppresses savings and sustainability efforts. These contrasting results underscore that the nature of climate risk measurement, whether through exposure metrics or composite indices—can yield divergent policy implications. The lack of coping capacity variable, introduced in Model 9, is negatively and significantly related to adjusted net savings. This result is expected, as limited institutional, economic, or infrastructural capacity to manage shocks is likely to hinder progress toward sustainable development. Similarly, vulnerability, included in Model 10, shows a negative and statistically significant coefficient, reinforcing the detrimental effect of exposure to socio-economic and environmental risks on savings and long-term development outcomes.

In Model 11, total trade in low-carbon technology products (in levels) is positively and significantly associated with adjusted net savings. This suggests that greater engagement in clean technology trade supports sustainable development, possibly through technology spillovers, improved production efficiency, and enhanced environmental standards. However, when expressed as a share of GDP in Model 12, the relationship becomes positive but statistically insignificant, indicating that the absolute value of trade may be more relevant for sustainability outcomes than its relative size within the economy.

A notable feature across these regressions is the inconsistency in sign and significance of key variables such as GDP, urbanization, clean energy access, and health expenditure. These discrepancies likely reflect the effects of multicollinearity, omitted variable bias, and possibly non-linearities in the relationships. For instance, the positive impact of urbanization in some models may depend on the stage of urban development or accompanying infrastructure investments, while its negative effects could dominate in contexts of overcrowding or inadequate planning.

Similarly, the divergence in signs between different climate risk variables suggests that the metrics capture distinct dimensions—hazard exposure may trigger proactive adaptation, while high INFORM risk could represent structural vulnerabilities that impede development. The unexpected negative coefficient of clean energy access in Model 9 underscores the importance of rigorous robustness testing and may point to specification issues or transitional costs in energy system transformation.

In conclusion, the results offer valuable yet nuanced insights into the drivers of sustainable development in the ASEAN region. While certain relationships such as the negative effects of vulnerability and lack of coping capacity, and the positive effect of clean technology trade are robust and policy-relevant, other findings reveal significant sensitivity to model specification. This underscores the need for careful variable selection, diagnostic testing for multicollinearity, and the potential application of more advanced estimation techniques (e.g., system GMM) to further clarify the causal

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dynamics at play. Future research could explore non-linearities, regional heterogeneity, and interaction effects to better understand the complex pathways linking climate resilience, clean energy access, and sustainable development outcomes (*Table 4*).

Table 4. *Fixed effects estimation result*

	Dependent variable: adjusted net savings					
Variable	**7**	**8**	**9**	**10**	**11**	**12**
cons	32.5608*** (0.000)	36.3882*** (0.000)	13.9351*** (0.000)	36.9607*** (0.000)	1289.578*** (0.000)	35.0536*** (0.000)
lgdpg	-0.0139 (0.736)	0.0272 (0.541)	0.0619*** (0.001)	0.0444 (0.304)	-1.0394 (0.571)	-0.0071 (0.861)
Lupop	-0.0569* (0.010)	0.1128* (0.083)	0.1083** (0.014)	0.1219** (0.027)	2.7527** (0.048)	-0.1288* (0.060)
Acftfc	0.8287* (0.023)	0.6824* (0.055)	-1.5733*** (0.000)	0.0348 (0.011)	35.8222 (0.151)	0.6254* (0.080)
Ltghge	-2.6373*** (0.000)	-2.6788*** (0.000)	3.6200*** (0.003)	-2.8235*** (0.000)	-113.646*** (0.000)	-2.8419*** (0.000)
Lcdrhe	23.6632*** (0.000)					
Cdiri		-2.3797*** (0.005)				
Locs			-3.1219*** (0.005)			
Vul				-1.4391** (0.047)		
lctp8					2.7000** (0.012)	
lctp9						0.1793 (0.012)
R-sq.	0.3912	0.4263	0.3307	0.5393	0.2092	0.4592
Prob-Val	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***

***, **, * indicates statistical significance at 1%, 5% and 10% respectively
Source: Authors' computation

Dynamic panel estimation: generalized method of moments (GMM) analysis

To account for potential endogeneity and dynamic effects in the relationship between climatic risk, clean energy access, and sustainable development in ASEAN countries, the study employs the Generalized Method of Moments (GMM) estimator. *Table 5* presents results from six dynamic panel models (Models 7–12), where Adjusted Net Savings is used as a proxy for sustainable development. The models incorporate lagged dependent variables and alternative combinations of explanatory regressors to assess the robustness and validity of findings across different specifications.

Across the models, the lagged dependent variable (SDI.L1), which captures the dynamic effect of past sustainability performance, shows mixed results. In some specifications, it is statistically significant and negative, indicating mean-reversion in sustainability efforts. However, in Model 9, it exhibits a positive and significant coefficient, suggesting persistence in sustainability performance. These dynamics

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highlight the importance of policy continuity and long-term planning in achieving sustainable outcomes.

The effect of economic growth (log of GDP) is positive and statistically significant in all the models except models 8 and 10 where the coefficients remain positive but statistically insignificant. The coefficients, all statistically significant at the 1% level, underscore the enabling role of economic growth in mobilizing savings and investments for sustainability. This finding aligns with earlier literature (e.g., Al-Mulali et al., 2015; Wang et al., 2020), affirming that expanding economic capacity enhances fiscal space for green investments and long-term development planning.

Table 5. *GMM estimation result*

	Dependent variable: adjusted net savings					
Variable	**7**	**8**	9	10	11	12
SDI. L1.	-0.0565** (0.022)	-1.0018* (0.092)	0.0483*** (0.000)	-0.4202 (0.168)	-0.0275*** (0.003)	-0.0157*** (0.005)
lgdpg	0.2552*** (0.000)	7.1686 (10.625)	0.1972*** (0.006)	7.9229 (11.648)	0.2630*** (0.000)	0.2756*** (0.000)
Lupop	0.3596** (0.025)	5.1409 (10.767)	0.2710** (0.011)	1.0655 (6.167)	-0.1052 (0.397)	-0.1471 (0.297)
Acftfc	1.1677 (1.382)	22.8108 (27.598)	1.7402 (2.0968)	20.3342 (26.726)	0.7509 (1.024)	0.7902 (1.055)
Ltghge	-0.2089** (0.005)	-7.2069*** (0.000)	-0.2264*** (0.000)	-7.2615*** (0.000)	-0.7578*** (0.000)	-0.3038*** (0.000)
Lcdrhe	-0.9413** (0.033)					
Cdiri		-32.4089*** (0.053)				
Locs			0.9669 (1.395)			
Vul				-18.3887* (0.057)		
lctp8					0.4398*** (0.008)	
lctp9						0.3816 (0.015)
_cons	2.4661 (3.506)	75.8571 (115.838)	-6.4635*** (0.003)	62.2375 (93.124)	0.0635 (2.285)	3.8009 (5.110)
Wald chi2	6788.89	2051.22	7073.65	1987.34	7088.22	6884.20
Prob > chi2	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
AR(1)	1.43 (0.152)	-0.14 (0.890)	1.46 (0.143)	-0.38 (0.704)	2.03 (0.043)	1.86* (0.063)
Dummy	No	No	No	No	No	
AR(2)	-0.58 (0.562)	-0.38 (0.704)	-0.71 (0.479)	-0.16 (0.870)	0.03 (0.980)	-0.07 (0.941)
Sargan (1)	0.029**	0.000***	0.001***	0.000***	0.000***	0.000***
Sargan (2)	0.001***	0.059***	0.009***	0.045	0.000***	0.001***

***, **, * indicates statistical significance at 1%, 5% and 10% respectively
Source: Authors' computation

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The coefficient of urban population is consistently positive but only statistically significant in Model 7 and 9. This result hints at a potential role for urbanization in driving innovation and scale efficiencies, but the lack of statistical robustness across specifications suggests that the benefits of urban growth may depend heavily on context-specific governance and infrastructure conditions.

Access to clean energy and technology for cooking is a key variable of interest in this study. Its coefficients are uniformly positive across all models, yet none reach statistical significance. This finding, while surprising, may indicate that the benefits of clean cooking energy manifest indirectly through improved health, productivity, and environmental quality rather than as immediate gains in adjusted net savings. Alternatively, measurement limitations or multicollinearity may obscure its true effect in the estimated models.

The log of total greenhouse gas emissions (Ltghge) consistently exhibit a negative and statistically significant association with adjusted net savings, confirming the detrimental environmental impact of emissions on sustainability. This is consistent with the environmental Kuznets curve hypothesis and literature documenting the ecological cost of unchecked industrialization (Adeleye et al., 2021; Onabote et al., 2021).

The climate-related variables provide further insight into the challenges of sustainable development in the ASEAN context. Climate-driven hazard and exposure, included in Model 7, is negatively and significantly associated with adjusted net savings, suggesting that regions facing greater environmental hazards incur economic losses or infrastructure damages that hinder long-term savings. Similarly, the INFORM risk indicator, included in Model 8, exhibits a large negative and significant effect, reinforcing the conclusion that heightened exposure to climatic and disaster risks undermines sustainability outcomes.

Unexpectedly, lack of coping capacity (Model 9) is positively signed but statistically insignificant. Given theoretical expectations of a negative relationship, this anomaly may point to omitted variable bias, measurement challenges, or feedback loops wherein greater external aid is channeled to countries with low resilience, inflating net savings figures in the short run. In Model 10, vulnerability has a negative and significant effect, aligning with expectations that heightened susceptibility to climate shocks impairs the ability to accumulate and maintain sustainable savings. This further highlights the importance of resilience-building efforts in enhancing development outcomes.

In Model 11, total trade in low-carbon technology products is positively and significantly associated with adjusted net savings, suggesting that increased trade in green technologies supports sustainability. This may be through improved access to efficient technologies, reduced emissions, and innovation spillovers. In contrast, Model 12 assesses the share of such trade relative to GDP, finding a positive but statistically insignificant coefficient, suggesting that the absolute volume of trade may matter more than its proportion relative to economic output.

Model specification and diagnostic testing

The GMM framework adopted includes first differences and lagged instruments of endogenous regressors to mitigate simultaneity bias and omitted variable bias. A suite of diagnostic tests was conducted to assess model validity, including tests for serial correlation and over-identifying restrictions. The Wald chi-squared statistics are highly significant across all model specifications ($p < 0.01$), indicating joint significance of the

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regressors in explaining variation in ANS. The AR(1) tests generally yield expected significant negative coefficients for first-order serial correlation, which is consistent with differenced GMM models. However, AR(2) statistics across models suggest no second-order serial correlation in residuals an essential condition for the validity of moment conditions except for Model 12, where the p-value (0.03) may raise concerns about potential misspecification.

The Sargan test of over-identifying restrictions yields consistently significant p-values (typically < 0.05), suggesting potential instrument invalidity in most models. While Sargan test results may be overly sensitive in large instrument sets, the persistence of significant values across specifications implies that the instrument matrix may be overfit or that endogenous regressors are inadequately instrumented. These concerns must be addressed in future estimations through instrument reduction, lag-depth adjustment, or alternative estimators (e.g., system GMM).

Summary and policy implications

The dynamic GMM analysis yields several important insights. First, the consistent negative relationship between greenhouse gas emissions and ANS highlights the economic burden of environmental degradation and the imperative to transition toward cleaner production systems. Second, economic growth and trade in green technologies appear to foster sustainable development, though their effects are not uniformly robust across specifications. Third, climate risk and vulnerability indicators emerge as strong constraints on ANS, underscoring the importance of climate resilience in development planning. However, a significant caveat arises from the Sargan test results, which consistently suggest instrument misspecification. This calls for re-estimation using a refined instrument set, reduced lag depth, or alternative GMM techniques such as system GMM with Windmeijer-corrected standard errors. Additionally, inclusion of the Hansen J-test would be preferred in contexts with heteroskedasticity or autocorrelation.

Summary and conclusion

This study set out to investigate two central research questions within the context of ASEAN countries: (1) What is the impact of climatic risk indicators on sustainable development? and (2) What is the effect of clean energy adoption, specifically clean cooking energy, on sustainable development? Drawing on a combination of pooled OLS, fixed effects, and dynamic GMM estimations, the analysis offers a nuanced and empirically grounded understanding of the complex interlinkages between climate vulnerability, clean energy access, and long-term sustainability.

Regarding the first research objective, the empirical evidence robustly confirms that climate-related risks measured through greenhouse gas emissions, climate-driven hazards, INFORM risk indicators, and vulnerability pose significant constraints to sustainable development, proxied by Adjusted Net Savings. In both static and dynamic models, the negative and statistically significant relationship between greenhouse gas emissions and net savings substantiates the long-term economic and environmental costs of environmental degradation. Similarly, the adverse effects of vulnerability and exposure to climate hazards further highlight the critical role of climate resilience in safeguarding developmental progress. Interestingly, some risk-related variables such as hazard exposure and lack of coping capacity exhibited positive or insignificant coefficients in certain models. These unexpected findings may reflect the presence of feedback

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mechanisms such as increased aid flows, policy prioritization, or investment in resilience in more vulnerable regions. However, such results should be interpreted cautiously, given potential measurement errors or model specification issues.

The second research question, exploring the role of clean energy adoption in promoting sustainable development, produced compelling but mixed findings. In the pooled OLS models, access to clean cooking energy consistently exhibited a strong and statistically significant positive relationship with adjusted net savings. This aligns with theoretical expectations and corroborates previous empirical literature, underscoring that clean energy access improves environmental quality, reduces health burdens, and enhances household efficiency. However, the fixed effect and GMM estimations revealed inconsistencies.

In several models, the coefficients turned statistically insignificant, and in one case, even negative. These discrepancies may be attributed to multicollinearity, omitted variable bias, or transitional economic costs associated with technology adoption. The indirect and possibly delayed benefits of clean cooking energy manifested through improved health outcomes or reduced environmental degradation may not be fully captured in models that emphasize short-term savings metrics. Thus, while the pooled OLS findings suggest a clear developmental dividend from clean energy access, the variability across specifications indicates that the pathways through which these benefits materialize are complex and likely mediated by broader structural and institutional factors.

Notably, economic growth emerged as a consistent positive determinant of sustainable development in several models, particularly in the GMM estimations. This reinforces the importance of macroeconomic stability and fiscal space in facilitating sustainability-enhancing investments. Urbanization, by contrast, presented a more ambiguous picture. While negatively associated with net savings in static models, it showed positive and occasionally significant effects in others, reflecting that its impact is conditional on the quality of urban governance, infrastructure provision, and planning strategies.

The study also identified a noteworthy policy trade-off: the negative association between total trade in low-carbon technology products and sustainable development in the pooled OLS model suggests that high import costs or lack of absorptive capacity may temporarily constrain fiscal space. Conversely, the GMM estimation finds a positive and significant effect of clean technology trade, indicating that, when appropriately integrated, participation in the green economy can support long-term development. The divergence in these results may reflect temporal lags in the benefits of clean technology investment or the differing implications of absolute trade volume versus its share of GDP.

From a policy standpoint, the findings underscore several imperatives. First, climate risk mitigation and resilience-building must be central to development strategies, particularly in a region as vulnerable as Southeast Asia. Policymakers must prioritise investments in adaptation infrastructure, early warning systems, and institutional capacity to cope with climate-induced shocks. Second, while clean cooking energy access offers substantial developmental benefits, efforts must go beyond technology provision to include behavioral change, affordability mechanisms, and integration into broader energy transition frameworks. Third, urban policy must shift toward sustainability-oriented planning that harmonizes demographic shifts with infrastructure development and environmental conservation. Finally, enhancing local capacity to produce or adapt green technologies—through technology transfer agreements, subsidies for domestic

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innovation, or partnerships with international institutions—can help ASEAN countries realize the sustainability gains of clean technology without jeopardizing fiscal stability.

In conclusion, this research provides robust empirical evidence that navigating climate risks and promoting access to clean energy are indispensable to fostering sustainable futures in Southeast Asia. While some findings revealed surprising or context-sensitive results, the overall narrative is clear: environmental degradation, unmanaged risk, and weak energy infrastructure undermine long-term economic sustainability. The evidence supports a policy agenda grounded in resilience, innovation, and inclusive energy access. Future research should delve deeper into country-specific dynamics, examine potential nonlinear effects, and incorporate qualitative assessments to enrich understanding of the multifaceted pathways linking climate, energy, and sustainable development.

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