



## Nexus between environmental innovation, energy efficiency and environmental sustainability in Southeast Asian economy

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### Abstract

Every major event on a national or worldwide scale has some kind of environmental effect, and researchers are always looking for new strategies to lessen the destruction of ecosystems. Experts have proposed and executed policy options for energy adaptation and integration, such as the use of renewable energy, throughout the last decade. The study examines the relationship between environmental innovation, energy efficiency, and institutional quality in Southeast Asia from 1980 to 2020. The empirical relationship was evaluated using autoregressive distributed lag (ARDL), cross-sectional ARDL, and Dumitrescu-hurling models. Similarities in the dynamics of the variables led to the merging of the stationary ones after the initial difference was found. Long-term correlation between variables was confirmed using the panel counteraction test. Integration of renewable energy sources and environmental innovation improve the long-term viability of Southeast Asia's economy, as shown by the ARDL and CS-ARDL variable coefficients. Inductees who are environmentally savvy and efficient have a greater impact on environmental policy when their institutions are strong. There is a well-established feedback loop between renewable energy and environmental sustainability. There is a clear causal relationship between institutional quality and environmental sustainability. The research recommended that in order to achieve environmental sustainability, governments and policymakers increase the use of renewable energy sources and invest in environmental innovation.

**Keywords:** Environmental Innovation; Energy Efficiency; Institutional Quality; Environmental Sustainability; ARDL; CS-ARDL

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### 1. Introduction

Because the detrimental impacts of environmental degradation, such as climate change and global warming, have begun to show globally, countries are forced to look for a collective solution to this problem. Existing research on environmental quality reveals that increasing environmental quality involves two courses of action: a macro-fundamental contribution and energy policies focused on integrating renewable energy sources as opposed to fossil fuels. [Citation needed] (Cardenas *et al.*, 2016; Shi & Qamruzzaman, 2022) <sup>[22]</sup>. According to Apergis *et al.* (2010) <sup>[14]</sup>, stringent energy rules impede economic development. This is the case even though the incorporation of clean energy reduces carbon emissions and, as a result, improves environmental quality. Therefore, the challenge of conservative energy policy and economic development has prompted policymakers to adopt an environmental policy that reconciles environmental quality and economic growth via the management of energy integration, preferably through renewable energy sources. This policy seeks to achieve this reconciliation through using renewable energy sources. In economics, the deterioration of the environment is an important problem that has received a great deal of attention from economists, academics, and researchers over the last few decades. There has been a steady increase in carbon emissions, and as a result, there have been dangers to both human health and the environment. As a result of these concerns, nations face significant implications due to global warming (Lanouar *et al.*, 2016) <sup>[46]</sup>. Researchers have emphasized research into the key factors that contribute to mitigating the present climate change crisis to increase environmental sustainability by reducing the harmful effects of greenhouse gas (GHG) emissions into the atmosphere.

This is done to achieve the goal of increasing environmental sustainability (Adebayo & Kirikkaleli, 2021a) <sup>[3]</sup>.

During the phase of economic expansion, thorough industrialization and domestic aggregation cause substantial carbon emissions due to a heavy reliance on fossil fuels rather than renewable energy. In addition, the government has ignored the ultimate consequence by focusing solely on economic development. This is because fossil fuels are the primary energy source for most industrial processes. In recent years, several factors contributing to the deterioration of the environment have come to light, and governments are now making efforts to address issues connected to the environment's quality (Khan *et al.*, 2021) <sup>[9]</sup>. There is a widespread consensus that climate change and global warming are at least partially caused by carbon dioxide emissions (CO<sub>2</sub>). The safety of the environment has always been of the utmost significance in South Asia; it impacts both the quantity of food produced by agriculture and the lives of millions of people daily (Andriamahery & Qamruzzaman, 2022) <sup>[12]</sup>.

The present study contributes to the existing literature in the following ground. First, according to existing literature surrounding environmental degradation and sustainability, researchers and academicians have invested their time and efforts in unleashing the way of lessening the environmental adversity with the accommodation of green energy and policy implementation. In managing environmental diversification for sustainability, a growing number of researchers have examined the role of environmental innovation, energy efficiency and good governance by taking into account either country specifics or/and panel data (Adebayo & Kirikkaleli, 2021a; Alsahlawi *et al.*, 2021; Khan *et al.*, 2021; Md, 2021; Nepal *et al.*, 2021; Qamruzzaman, 2021; Zhang *et al.*, 2021) <sup>[3, 10, 9, 11, 61, 29, 40, 103]</sup>. However, focusing on environmental Sustainability in Southeast Asian economies, very few studies have been performed in empirical assessment see, for instance (Amin *et al.*, 2021; Hasnat *et al.*, 2018; Murshed, 2020; Qamruzzaman, 2022c) <sup>[11, 33, 59, 79]</sup>. With our best knowledge, for the first time, the nexus between environmental sustainability, environmental innovation, energy efficiency, and institutional quality in the Southeast Asian economy has been investigated.

This study examines the impact of environmental innovation, energy efficiency, and institutional quality on environmental sustainability management in the Southeast Asian economy between 1980 and 2020. A cross-sectional dependency test, long-run cointegration using an error correction model, baseline estimation with random effects and fixed effects model, explanatory variables magnitudes on environmental sustainability detected via ARDL and CS-ARDL, and directional causality was implemented in the Study. The Study's results demonstrated that research units shared a dynamic and heterogeneous nature. Variables stay unchanged after the first difference, but neither is exposed to the second difference, as is desirable for robust estimation.

The remaining stricture of the article is as follows: Section I deals with the background of the Study, and the literature review and hypothesis development are available in Section II. Section III reports the data, variables definition, and methodology of the Study. Section IV displays the empirical model estimation and discussion, and the conclusion and policy suggestions are finely exhibited.

## 2. Literature review

*Environmental innovation and environmental sustainability*  
Using a technique known as the system generalized method of moments (SGMM), Zhang *et al.* (2017) <sup>[102]</sup> investigated the impact that technological advancements in the field of environmental protection had on China's carbon emissions from 2000 to 2013. This research examines the relationship between technological advancement in environmental protection and long-term environmental preservation. As shown by the Study's conclusions, the bulk of the environmental innovation aspects reportedly applies a considerable effect to decreasing carbon emissions successfully. Paramati *et al.* (2021) <sup>[63]</sup> investigated the role of per capita income, foreign direct investment (FDI), green technology, trade openness, and financial deepening on carbon emissions in a panel of 25 OECD countries from 1991 to 2016. They use cross-sectional dependence (CD) and cross-sectional augmented Im-Pesaran-Shin (CIPS) tests. This inquiry focuses on the nations that are members of the OECD, covering the years 1991 to 2016. According to the Study's conclusions, there is a possibility that carbon emissions might be lowered by expanding the openness of commerce, the use of environmentally friendly technologies, and the flows of foreign direct investment.

On the other hand, a rise in both financial depth and income per capita leads to increased carbon emissions. This is the case regardless of the kind of growth. The resource-based and natural resource-based views were utilized in Lee and Min's (2015) <sup>[49]</sup> and Qamruzzaman's (2022b) <sup>[78]</sup> analyses to determine the impact of green research and development investment on eco-innovation on the environment and the financial performance of Japanese manufacturing firms from 2001 to 2010. This was done to determine the impact of green research and development investment for eco-innovation on Japanese manufacturing firms from 2001 to 2010. From 2001 till 2010, this was the period that was taken into account. The results of the Study indicate that there is a corrosive link between environmentally friendly research and development and carbon emissions. In addition, Shahbaz *et al.* (2018) <sup>[16]</sup> offered evidence to support the claim that the development of new energy sources contributes favorably to decreasing CO<sub>2</sub> emissions, which in turn serves to enhance the overall quality of the environment.

Kneifel (2010) <sup>[45]</sup> urged incorporating energy-efficient technology to enhance environmental sustainability by reducing energy intensity and, eventually, carbon emissions. Using conventional energy efficiency technologies, the energy use/consumption of new commercial buildings can be lowered by an average of 20 to 30 percent, according to the Study. For some building types and environments, the decline might exceed 40 percent. These enhancements reduce a building's carbon footprint by an average of 16 percent while saving money and energy. According to Lantz and Feng (2006) <sup>[47]</sup>, the relationship between technology and carbon dioxide is U-shaped. In addition, Adebayo *et al.* (2022) <sup>[6]</sup> discovered an asymmetric link between technological innovation and environmental sustainability, with positive (negative) technological innovation shocks resulting in a decrease (increase) in Sweden's carbon emissions.

Adebayo *et al.* (2021) <sup>[5]</sup> employed the Morlet wavelet technique to evaluate the link between renewable energy utilization, technological innovation, and carbon emissions in

Portugal between 1980 and 2019. According to the Study's findings, the connection of indicators rises with time and frequency. In addition, this analysis reveals strong wavelet coherence and significant lead and lag linkages in the frequency domain but contradicting interactions between the variables in the time domain. Even though trade openness, technological innovation, and economic expansion contribute to CO<sub>2</sub> emissions, Wavelet research shows that using renewable energy helps decrease CO<sub>2</sub> emissions. Using wavelet analysis in Japan, Adebayo and Kirikkaleli (2021b)<sup>[4]</sup> and Xia *et al.* (2022)<sup>[96]</sup> postulated that globalization, GDP growth, and technological innovation increase CO<sub>2</sub> emissions in Japan, but that renewable energy consumption mitigates CO<sub>2</sub> emissions in the short and medium future.

#### *Energy efficiency and environmental sustainability*

According to the Energy efficiency and environmental sustainability nexus, a growing number of research have shown a positive and statistically significant correlation between energy efficiency and environmental sustainability. See Akram *et al.* (2020)<sup>[8]</sup>, Hanley *et al.* (2009)<sup>[32]</sup>, Qamruzzaman (2015)<sup>[74]</sup>. According to Sarkodie and Strezov's (2019)<sup>[88]</sup> study, energy use significantly impact greenhouse gas emissions. Reducing greenhouse gas emissions requires increased energy efficiency, using clean and contemporary technologies such as renewable energy and nuclear power, and carbon capture and storage in fossil fuel and biomass energy-generating processes.

Balsalobre-Lorente *et al.* (2018)<sup>[16]</sup> examine the link between economic development, energy innovation, renewable power consumption, natural resource availability, trade openness, and carbon dioxide emissions in five nations between 1985 and 2016. (Germany, France, Italy, Spain, and the United Kingdom). The research shows that using renewable energy, energy innovation, and natural resources enhances environmental quality. Trade liberalization, on the other hand, and the link between economic development and renewable energy consumption positively impact carbon dioxide emissions. Boutabba (2014)<sup>[18]</sup> used the Granger Causality Test to examine the long-term equilibrium as well as the presence and direction of a causal link between carbon emissions, energy consumption, financial development, trade openness, and economic growth in India from 1971 to 2008. The research found a long-term causal relationship between per capita carbon emissions and per capita energy usage. After controlling for several factors, Sun *et al.* (2019)<sup>[92]</sup> showed that green innovation and institutional quality substantially affected energy efficiency improvement. Between 1980 and 1997, Brannlund *et al.* (2007) explore how external technical development in the form of increased energy efficiency affects the consumption decisions of Swedish households and, as a result, their carbon dioxide and sulfur emissions and nitrogen oxide. According to the research, a 20% improvement in energy efficiency would reduce CO<sub>2</sub> emissions by 5%. Miao *et al.* (2022)<sup>[58]</sup> used the Method of Moments Quantile Regression on yearly data from 1990 to 2018 to study the relationship between renewable energy use, globalization, and ecological footprint in newly industrialized countries (NICs). (MMQR). The outcomes of this study demonstrate the favorable and statistically significant impact of financial globalization and renewable energy use on environmental quality improvement.

#### **Institutional quality and environmental sustainability**

Third, Abid (2017)<sup>[2]</sup> investigates the impact of institutional, financial, and economic changes on the rate of environmental degradation in 41 E.U. countries and 58 MEA countries between 1990 and 2011. Environmental sustainability and institutional quality are the topics that are covered in this research. According to this study's findings, robust institutions have both a direct and an indirect impact on economic growth and environmental quality in the countries that make up the E.U. They do this by enhancing the efficiency of public spending, fostering financial development, and encouraging direct investment from other countries. In a separate piece of research, Lau *et al.* (2014)<sup>[48]</sup> used Granger causality tests and the autoregressive distributed lag (ARDL) limits testing technique to investigate the causative relationships between CO<sub>2</sub> emissions, exports, and institutional quality, and economic development in Malaysia from 1984 to 2008. The period under investigation was from 1984 to 2008. The findings of the study point to the existence of a correlation sustained through time between the variables. One of the conclusions that can be drawn from this is that maintaining a high level of institutional quality is necessary to curb CO<sub>2</sub> emissions and foster economic growth. Granger causality testing provides more data demonstrating the significance of institutional frameworks in reducing carbon dioxide emissions. In line with the findings that were uncovered via the investigation conducted by Bhattacharya *et al.* (2017)<sup>[41]</sup>. According to Abid (2016)<sup>[1]</sup>, factors like political stability, democracy, the effectiveness of the administration, and the avoidance of corruption all have a bearing on the amount of carbon dioxide released into the atmosphere. On the other hand, strong regulation and the rule of law positively impact the amount of carbon dioxide released into the atmosphere.

Ibrahim and Law (2016)<sup>[37]</sup> investigate the roles of institutional quality, trade and their interactivity in explaining CO<sub>2</sub> emissions for 40 Sub-Saharan African (SSA) countries for the period 2000 to 2010 by applying the system generalized method of moments (GMM). Study unveils trade and institutional quality is beneficial to environmental sustainability. The study also suggested that institutional reforms explicitly support excelling the environmental status. However, trade openness is detrimental to the environment in countries with poor institutional quality and helpful in those with high institutional quality. Sarpong and Bein (2020)<sup>[89]</sup> apply the generalized moment (GMM) method in assessing the nexus between CO<sub>2</sub> and good governance with a panel of 38 oil- and non-oil-producing nations in the Sub-Saharan Africa region from 2005 to 2014. The Study divulges that good governance is the bestow in manage carbon emissions in enduring Environmental Sustainability. Countries have a good governance structure that aids in controlling and reducing CO<sub>2</sub> emissions.

Furthermore, there is a positive correlation between government administration quality and CO<sub>2</sub> emissions in oil-producing nations, but in non-oil-producing countries, the correlation is negative. Liu *et al.* (2020)<sup>[52]</sup> document that political, economic and institutional governance substantially negatively affect CO<sub>2</sub> emissions, reducing pollution levels. Empirical results also reveal that government effectiveness is helpful in the reduction of CO<sub>2</sub> emissions in high carbon-

emitting nations.

### 3. Data and methodology of the Study

#### 3.1 Model specification

Environmental sustainability has been a growing concern for everybody. Therefore, many researchers have invested their time in exploring the key determinants for managing environmental costs over the past decades. In the line of empirical investigation, researchers have documented several critical macro fundamentals in environmental protection; however, their role in environmental sustainability differs from geographical and economic structural changes. The motivation of the study is to gauge the role of energy efficiency, environmental innovation, and institutional quality in managing environmental sustainability, that is, do all the explanatory variables augment or degrade the environmental sustainability in the Southeast Asian economy. The generalized empirical model is as follows:

$$E.S. (CO_2, E.F.) | E.E., E.I., I.Q. \quad (1)$$

Where E.S. stands for environmental Sustainability, E.E. explains energy efficiency, E.I. for environmental innovation, and I.Q. denotes institutional quality. The variables proxies and data sources are displayed in table -1.

$$ES(co_2) = \alpha_0 + \beta_1 EE_{it} + \beta_2 EI_{it} + \beta_3 IQ_{it} + \beta_4 FDI_{it} + \beta_5 FDI_{it} + \varepsilon_{i,t} \quad (2)$$

$$ES(EF) = \alpha_0 + \gamma_1 EE_{it} + \gamma_2 EI_{it} + \gamma_3 IQ_{it} + \gamma_4 FDI_{it} + \gamma_5 FDI_{it} + \varepsilon_{i,t} \quad (3)$$

#### 3.2 Variables and descriptive statistics

##### Environmental Sustainability

Environmental sustainability is concerned with developing strategies to guarantee that economic development is sustainable without degrading environmental quality since it is undesirable to encourage economic growth at the price of environmental degradation. In light of this, the challenge of environmental protection over the last several decades has been adopting clean energy in industrial production to reduce the number of carbon emissions in the atmosphere. Environmental sustainability was measured by ecological footprints and carbon emissions (Hongxing *et al.*, 2021; Khan *et al.*, 2021; Qamruzzaman, 2021a, 2021b)<sup>[35, 9, 76]</sup> (Hussain & Dogan, 2021; Murshed *et al.*, 2021)<sup>[36, 60]</sup>. We studied the current literature and assessed both proxies in measuring environmental sustainability to study the complete and comparative assessment.

##### Energy efficiency

Energy efficiency has recently emerged as a tool in the field of energy management for lowering carbon emissions via the use of renewable power sources. The shift from conventional to renewable energy sources affects the quality of the environment, environmentally friendly industrial output, and economic development. Large sums of money are needed to diversify the energy sector with renewables. Costly initial expenditures make it difficult to transition to renewable energy sources to power the economy rapidly. In the present literature, there is no mention of any metrics for evaluating energy efficiency. We offered the proportion of renewable energy to fossil fuel consumption after carefully evaluating the concept and motivation of energy efficiency. As the ratio rises, energy efficiency and carbon dioxide emissions decrease.

#### Environmental innovation

Environmental innovation includes adopting and using carbon emission reduction and renewable energy technology. When we talk about environmental innovation (E.I.), we are talking about the spread and adaptation of cutting-edge technologies and practices related to the environment and the climate. Environmental innovation is at the root of the regulatory-adoption link; fear of greater regulation likely leads to more innovation. According to research conducted by Carrión-Flores and Innes (2010)<sup>[23]</sup>, the adoption of environmental technology by businesses is linked to the level of innovation inside such businesses (Popp, 2010)<sup>[73]</sup>. Regulatory rigor facilitates the adoption of sophisticated technologies, providing for improved consistency (Popp *et al.*, 2010)<sup>[73]</sup>. (Popp *et al.*, 2010)<sup>[73]</sup>. In literature measuring the effects of environmental innovation on environmental sustainability or quality, two-line of research studies are available; first, a group of researchers measured environmental innovation by considering the number of patent applications extracted from the World development indicator (WDI) see Zhang *et al.* (2017)<sup>[102]</sup>; Töbelmann and Wendler (2020)<sup>[94]</sup>; Khan *et al.* (2021)<sup>[9]</sup>. (2019). (2019). Two surrogate measures examine the relationship between environmental innovation and environmental sustainability. It is hypothesized from the Study that there is a connection between high environmental quality and creative problem solving (Meng *et al.*, 2021)<sup>[56]</sup>.

#### 3.3 Estimation strategy

##### A. Anel Autoregressive Distributed Lagged (PARDL)

Pooled grouped Mean hereafter PGM. PGM can estimate both long-run and short-run magnitude by addressing heterogeneity issues. The following ARDL (p, q ...n) as an empirical structure:

$$ES_{it} = \epsilon_{it} + \sum_{j=1}^p \beta_{ij} ES_{i,t-j} + \sum_{j=0}^q \gamma_{ij} EE_{i,t-j} + \sum_{j=0}^q \rho_{ij} EI_{i,t-j} + \sum_{j=0}^q \pi_{ij} IQ_{i,t-j} + \epsilon_{it} \quad (18)$$

##### B. CS-ARDL

Note, nonetheless, that panel ARDL undertakes errors are cross-sectionally independent. Nevertheless, such perceived notions might produce spurious estimations in some situations and lead to badly predisposed estimates if the regressors' unobserved common factors are correlated (Fang & Qamruzzaman, 2021; Yang *et al.*, 2021; Zhuo & Qamruzzaman, 2021)<sup>[29, 97, 105]</sup>. Chudik and Pesaran (2015)<sup>[25]</sup> propose implementing Pesaran's (2006)<sup>[67]</sup> Common Correlated Effects (CCE) approach in the context of panel ARDL models. Pesaran (2006)<sup>[67]</sup> displays the average values used in the Equation to represent unobserved common factors as a proxy for dependent and independent variables. Therefore, when averaging equations (16) and (17) across time, we obtain.

$$\overline{ES}_{it} = \bar{\alpha}_{it} + \sum_{j=1}^p \bar{\beta}_{ij} \overline{ES}_{i,t-j} + \sum_{j=0}^q \bar{\gamma}_{ij} \bar{Q}_{i,t-j} + \bar{\omega}'_i G_t + \bar{\epsilon}_{it} \quad (22)$$

$$\text{Where, } \bar{\alpha}_{it} = \frac{\sum_{i=1}^N \alpha_i}{N}$$

$$\bar{ES}_{t-j} = \frac{\sum_i^N ES_{i,t-j}}{N}, \bar{\beta}_j = \frac{\sum_i^N \beta_{ij}}{N} \quad j = 0,1,2 \quad p$$

$$\bar{Q}_{t-j} = \frac{\sum_i^N Q_{i,t-j}}{N}, \bar{\gamma}_j = \frac{\sum_i^N \gamma_{ij}}{N}, \quad j = 0,1,2 \quad q$$

$$\bar{\omega}_j = \frac{\sum_{i=1}^N \omega_i}{N}, \bar{\epsilon}_t = \frac{\sum_{i=1}^N \epsilon_{i,t}}{N}$$

The error term,  $\epsilon_i$ , in Eq. (6) is independently distributed across time and countries, mean congregates to zero (i.e.,  $\bar{\epsilon}_t = 0$ ) in root mean square error as  $N \rightarrow \infty$ . Therefore, the linear effects of both dependent and independents can establish in the presence of cross-sectional dependence in  $\mu_i$ ,

$$ES = \bar{\alpha}_{it} + \sum_{j=1}^p \bar{\beta}_{ij} \bar{ES}_{i,t-j} + \sum_{j=0}^q \bar{\gamma}_{ij} \bar{Q}_{i,t-j} + \bar{\omega}'_t G_t$$

$$\bar{\omega}'_t G_t = \bar{ES}_{it} - \bar{\alpha}_{it} + \sum_{j=1}^p \bar{\beta}_{ij} \bar{ES}_{i,t-j} + \sum_{j=0}^q \bar{\gamma}_{ij} \bar{Q}_{i,t-j} \quad (23)$$

$$G_t = \bar{ES}_{it} - \bar{\alpha}_{it} + \sum_{j=1}^p \bar{\beta}_{ij} \bar{ES}_{i,t-j} + \sum_{j=0}^q \bar{\gamma}_{ij} \bar{Q}_{i,t-j} / \bar{\omega}'_t$$

Thus, the Panel CS-ARDL specification of Equation (2)

$$\bar{ES}_{it} = \epsilon_{it} + \sum_{j=1}^p \beta_{ij} \bar{ES}_{i,t-j} + \sum_{j=0}^q \gamma_{ij} \bar{Q}_{i,t-j} + \sum_{j=0}^p \bar{\delta}'_{tj} \bar{Z}_{i,t-j} + \epsilon_{it} \quad (24)$$

Where  $\bar{Z} = (\bar{EE}, \bar{EI}, \bar{IQ}, )$  and  $S_Z$  in the number of lagged cross-sectional average furthermore, Equation (24) can be reparametrized to the effects of ECM presentation of Panel CS-ARDL as follows:

$$\Delta ES_{it} = \alpha_i + \xi_i (ES_{it-1} - \omega'_t Q_{it-1}) + \sum_{j=1}^{M-1} \gamma_{ij} \Delta ES_{it-j} + \sum_{j=0}^{N-1} \beta_{ij} \Delta Q_{it-j} + \sum_{j=1}^p \lambda_j \bar{\Delta ES}_{i,t-j} + \sum_{j=0}^q \delta_j \bar{\Delta Q}_{i,t-j} + \sum_{j=0}^{S_Z} \bar{\delta}'_{tj} \bar{Z}_{i,t-j} + \mu_{it} \quad (25)$$

Where  $\bar{\Delta ES}_{t-j} = \frac{\sum_i \Delta ES_{i,t-j}}{N}$ ,  $\bar{\Delta Q}_{t-j} = \frac{\sum_i \Delta Q_{i,t-j}}{N}$

**4. Empirical model estimation and interpretation**

Before adopting the target model to explore the magnitudes of E.I., E.E., and I.Q. on E.S., the research did many econometrical tests, including slop of heterogeneity, cross-sectional dependence, unit root test, panel cointegration test, and baseline estimate. The slope of heterogeneity, cross-sectional dependence, panel cointegration test, and baseline estimation (Qamruzzaman & Karim, 2020). Table 3 shows that all test statistics are significantly based on cross-sectional dependency. The study units have cross-sectional dependence. We may assume the research units have a common energy. Pesaran and Yamagata (2008) [71] are credited for the homogeneity results, which are consistent with Table 3's null hypothesis of "homogeneity" (Panel B). Both the test and adjustment statistics are statistically significant, indicating study unit heterogeneity.

**Table 3:** Cross-sectional dependency and Homogeneity test

	Panel –A: Cross-sectional Dependency test				Panel-B: Slop of Homogeneity	
	$LM_{BP}$ (Breusch & Pagan, 1980)	$LM_{PS}$ Pesaran (2004) [66]	$CD_{PS}$ Pesaran (2006) [67]	$LM_{adj}$	$\Delta$	Adj. $\Delta$
ES1	266.011***	28.24***	124.972***	32.114***	25.997	110.562
ES2	320.732***	23.946***	102.682***	27.416***	91.453	151.527
EE	234.401***	27.139***	195.329***	24.093***	21.869	129.886
EI	278.193***	44.153***	146.765***	53.273***	80.688	118.078
IQ	358.137***	40.565***	249.579***	10.949***	35.555	73.362
FDI	228.358***	24.742***	127.764***	40.603***	16.862	109.993
FD	308.094***	43.824***	243.107***	50.704***	92.052	65.48

Following Gengenbach *et al.* (2009) [31], we used a panel unit root test known as CIPS and a panel unit root test devised by Pesaran (2007) [68] known as the Constrained Autocorrelation Dispersion Function (CADF) to assess the order of integration. According to Dogan *et al.* (2017) [27],

conventional panel unit root tests have limitations owing to the absence of cross-sectional independence. When cross-sectional independence is present, the CADF and CIPS unit root tests provide correct results. Table 4 presents the test results for unit roots in a panel.

**Table 4:** Panel unit root test results

	Panel –A: Conventional Unit root test					
	Levin, Lin & Chu t		Im, Pesaran and Shin W-stat		ADF - Fisher Chi-square	
	t	t&c	t	t&c	t	t&c
<i>Panel –A: At level</i>						
ES1	-3.393	-2.03	-2.668	-2.29	57.272	38.565
ES2	-1.481	-2.032	-2.286	-1.223	37.104	55.155
EE	-1.687	-0.651	-2.538	-3.874	31.961	59.815
EI	-3.224	-1.996	-3.842	-0.204	43.948	31.48
IQ	-2.396	-1.734	-0.666	-3.01	35.689	58.9
FDI	-3.546	-1.789	-3.421	-3.951	34.6	38.967
FD	-0.805	-0.807	-1.409	-3.227	30.685	58.415
<b>Panel –B: After the first difference</b>						
ES1	-9.515***	-11.385***	-17.665***	-5.982***	292.552***	157.276***
ES2	-8.044***	-19.031***	-11.67***	-5.166***	304.436***	163.429***
EE	-10.895***	-7.25***	-12.574***	-8.02***	309.773***	128.784***
EI	-6.27***	-20.052***	-6.223***	-7.935***	123.053***	169.395***
IQ	-11.788***	-14.429***	-7.843***	-5.275***	152.463***	108.2***
FDI	-11.053***	-21.47***	-21.253***	-5.144***	119.556***	98.118***

FD	-5.57***	-14.985***	-18.529***	-8.27***	170.637***	105.468***
<b>Panel –B: Unit root test with Cross-sectional dependency</b>						
	CIPS			CADF		
	At level		Δ	At level		Δ
ES1	-2.702		-3.186***	-1.055		-2.056***
ES2	-1.082		-7.292***	-1.739		-6.302***
EE	-2.467		-6.959***	-1.818		-5.561***
EI <sub>1</sub>	-2.747		-2.123***	-2.371		-2.995***
EI <sub>2</sub>	-1.074		-2.617***	-1.746		-2.292***
IQ	-1.9		-5.888***	-1.402		-6.052***
FDI	-1.338		-6.864***	-2.624		-6.502***
FD	-1.82		-5.742***	-2.271		-2.456***

The following study examined the long-run link between environmental sustainability, energy efficiency, environmental innovation, and institutional quality using classical (Pedroni, 2001, 2004) [64] and error correction-based panel cointegration tests (Westerlund, 2007) [95]. Table 5 shows long-term cointegration. Most Pedroni cointegration test data are statistically significant at a 1% level, suggesting rejection of the null hypothesis: "no-cointegration."

Alternately, links analyze variables through time. ADF test statistics demonstrated a long-run link by rejecting the null hypothesis. The Study used error-correction-based cointegration to produce more accurate findings. The study found links between environmental sustainability, energy efficiency, environmental innovation, and institutional quality in Southeast Asian countries.

**Table 5:** Results of panel cointegration test

<b>Model - 1: Environmental Sustainability measured by carbon emission</b>				
<b>Panel –A: Pedroni cointegration test</b>				
	(1)	(2)	(3)	(4)
Panel v-Statistic	1.915	2.581	2.392	2.493
Panel rho-Statistic	-4.035	-4.391	-4.795	-6.196
Panel PP-Statistic	-9.685	-10.516	-8.095	-9.973
Panel ADF-Statistic	-3.816	-4.332	-6.515	-5.442
Group rho-Statistic	-1.269	-1.555	-0.396	-0.312
Group PP-Statistic	-11.747	-9.951	-9.655	-8.445
Group ADF-Statistic	-7.331	-9.451	-6.312	-8.326
Panel v-Statistic	-10.945	-6.179	-10.449	-11.579
Panel rho-Statistic	-8.934	-7.583	-11.563	-7.578
Panel PP-Statistic	-10.089	-7.593	-10.858	-6.488
Panel ADF-Statistic	-4.378	-4.477	-3.658	-4.364
<b>Panel –B: Kao cointegration test</b>				
ADF	-2.9726***	-1.5814***	-2.8971***	-5.8228***
<b>Panel C: Error correction based panel cointegration test</b>				
Gt	-13.307***	-12.571***	-11.492***	-10.603***
Ga	-11.552***	-8.216***	-12.916***	-6.928***
Pt	-7.315***	-10.633***	-8.03***	-11.502***
Pa	-13.504***	-11.396***	-7.723***	-13.815***

Note: the superscripts of \*\*\* explain the statistical significance at a 1% significance level.

The Study evaluated the baseline model with random and fixed effects before estimating the target model using the more sophisticated econometric model. Baseline values for carbon emission and ecological footprint models are included in Table 6. According to Houseman test statistics, the fixed-effects model estimate is more efficient (Jianguo & Qamruzzaman, 2017; Qamruzzaman *et al.*, 2020) [41, 80]. (Jianguo & Qamruzzaman, 2017; Qamruzzaman *et al.*, 2020) [4, 80]. The Study indicated a negative link between energy

efficiency and environmental sustainability for both model assessments. Green technology integration aids environmental sustainability, and environmental innovation decreases environmental degradation. Both model evaluations demonstrate that ecological output lowers harmful environmental consequences. When carbon emission (ecological footprint) is a dependent variable, institutional quality and environmental sustainability are favorably (negatively) associated.

**Table 6:** Baseline estimation with fixed effects and random effects

Variable	Random effects	Fixed effects	Random effects	Fixed effects
<b>Panel-A: environmental sustainability measured by Carbon emission</b>				
	[1]	[2]	[3]	[4]
EE	0.083(0.0127) [6.527]	0.046(0.0071) [6.443]	-0.109(0.0089) [-12.122]	0.636(0.0759) [8.378]
EI <sub>1</sub>	0.088(0.0068) [12.894]		-0.163(0.0182) [-8.951]	
EI <sub>2</sub>		0.217(0.0353) [6.141]		0.09(0.0158) [5.678]
IQ	0.597(0.1246) [4.788]	0.373(0.0485) [7.68]	0.556(0.0617) [9.01]	0.742(0.1611) [4.603]
FDI	0.128(0.015) [8.488]	0.618(0.0714) [8.65]	0.687(0.0975) [7.046]	0.723(0.0648) [11.157]

FD	0.354(0.0529) [6.681]	-0.094(0.0083) [-11.221]	0.237(0.0273) [8.662]	-0.052(0.0049) [-10.444]
C	-0.205(0.0279) [-7.328]	0.54(0.0478) [11.288]	0.138(0.018) [7.666]	0.636(0.1024) [6.209]
H-test	11.541		25.671	
<b>Panel –B: environmental sustainability measured by ecological footprint</b>				
	[5]	[6]	[7]	[8]
EE	0.491(0.0598) [8.205]	-0.031(0.0053) [-5.826]	-0.025(0.0059) [-4.176]	0.033(0.0026) [12.28]
EI <sub>1</sub>	-0.212(0.0202) [-10.484]		-0.129(0.0189) [-6.817]	
EI <sub>2</sub>		0.471(0.0476) [9.88]		-0.087(0.0148) [-5.855]
IQ	0.267(0.0322) [8.268]	0.472(0.0516) [9.131]	0.423(0.0533) [7.934]	0.006(0.0008) [6.673]
FDI	0.522(0.0507) [10.277]	-0.206(0.0184) [-11.141]	0.548(0.061) [8.98]	0.132(0.0196) [6.731]
FD	0.497(0.119) [4.174]	0.668(0.053) [12.602]	0.719(0.1094) [6.569]	0.662(0.1487) [4.451]
C	0.124(0.024) [5.161]	0.227(0.0279) [8.109]	0.457(0.0379) [12.051]	0.365(0.0324) [11.25]
H-test	15.942		25.6148	

Note: the value in () represent standard effort and in [] denotes t-statistics.

With a coefficient of -0.1699(-0.0743), the study found a negative and statistically significant relationship between energy efficiency and environmental sustainability, suggesting that Southeast Asian nations can manage carbon emissions into the ecosystem by ensuring energy efficiency. This is because the energy transaction is from fossil fuel to renewable energy. More precisely, a 10% increase in energy efficiency can lower carbon emissions in the Southeast Asian economy by between 0.7439 and 1.699% of their present level. This is in line with what is known now, as shown by this research and others like it. In a nutshell, Riti and Shu (2001) [86], Qamruzzaman *et al.* (2022) [12], and Rosenfeld (1999) [87] all concur (2016). According to the interim study results, there is a statistically significant and negative (positive) association between energy efficiency and carbon emission (coefficient = -0.0415). (0.0462). Researchers showed that although there might be some negative environmental consequences from using more efficient energy sources, the beneficial development benefits were far more pronounced.

The application of ARDL to environmental sustainability (CS-ARDL) is at the crossroads of environmental innovation (E.I. hereafter). According to the coefficients from both estimations, the study revealed a negative and statistically significant tie with a coefficient of -0.1728 (-0.0876), implying that progress in environmental innovation aids in reducing the level of environmental adversity through the incorporation of environmentally friendly technology in industrial output, eventually decreasing carbon intensity in the economy. In terms of short-run evaluation, the study found a negative and statistically significant connection in both model estimations, with a value of -0.0361. (-0.0292). (-0.0292). Other scholars, like Zhang *et al.* (2017) [102], Töbelmann and Wendler (2020) [94], Zhao and Qamruzzaman (2022) [12], and Iqbal *et al.* (2021) [39], have found that environmental innovations are beneficial to environmental prosperity. In contrast to Khan *et al.* (2021) [11] and Qamruzzaman *et al.* (2022a) [77]. According to Hodson *et al.* (2018) [34], environmental innovation promotes successful energy integration by reducing energy costs and transition and improving environmental quality by cutting carbon emissions. Furthermore, Cagno *et al.* (2015) [74] argued that environmental innovation supports the economy by shifting energy reliance away from fossil fuels and toward renewable energy for industrial output, cutting carbon emissions.

ARDL (CS-ARDL) analysis found a negative and statistically significant relationship between institutional quality and environmental sustainability, with a value of -

0.1449 indicating the strength of this relationship (-0.0794). This shows that competent and efficient domestic institutions play a catalytic role in enhancing environmental development by cutting carbon emissions in the economy. This would be an important step toward achieving the Sustainable Development Goals. It is possible that an improvement in environmental quality in south Asia of 1.449% would result from an increase in institutional quality of 10%. (0.794 %). Khan *et al.* (2021) [43] and Tang *et al.* (2021) [39]. Abid (2017) [2] investigates the effect that economic, financial, and institutional shifts had on the state of the environment in 58 Middle Eastern and African countries and 41 European Union nations between the years 1990 and 2011. According to the Study's findings, the standard of institutions has both a direct and an indirect impact on economic growth and environmental quality in E.U. nations. This influence is manifested through the efficiency of public spending, the growth of the financial sector, and foreign direct investment. Lau *et al.* (2014) [48] explore the long-run link between CO<sub>2</sub> emission, exports, institutional quality, and economic development in Malaysia from 1984 to 2008 using autoregressive distributed lag (ARDL) bounds testing and Granger causality tests. This was done to examine the causal link between these elements (Yingjun *et al.*, 2021) [99]. The research indicates that there is a long-term connection between the components. In addition, a high level of institutional quality is essential if CO<sub>2</sub> emissions are to be controlled throughout the economic development process. Furthermore, Granger causality studies demonstrate the significance of institutional frameworks in reducing CO<sub>2</sub> emissions. In the same spirit as the findings provided in Bhattacharya *et al.* Study, 's we find that (2017) [17]. According to Abid (2016) [1], political stability, democracy, administrative efficiency, and corruption control all negatively affect CO<sub>2</sub> emissions. However, the quality of laws and the existence of the rule of law positively affect CO<sub>2</sub> emissions (Qamruzzaman & Wei, 2019) [85].

Regarding the impact of foreign direct investment on environmental sustainability, it is obvious that FDI inflows encourage green energy integration and increase operational efficiency, therefore mitigating the negative effects of environmental degradation. In particular, an increase of 10 percent in FDI inflows may enhance environmental quality by reducing carbon emissions by 0.0412 to 0.0155 percent. Tang *et al.* (2021) [39] and Zafar *et al.* (2020) [100] support our Study's findings; however, Zafar *et al.* findings.'s contradict ours (2020) [100].

**Table 7:** Environmental sustainability measured by CO<sub>2</sub> emission

	ARDL [1]	CS-ARDL [2]	ARDL [3]	CS-ARDL [4]
EE	-0.1699(0.0968) [-1.7548]	-0.0743(0.0168) [-4.4037]	0.1046(0.05) [2.0902]	0.1056(0.0162) [6.4901]
EI <sub>1</sub>	-0.1728(0.0546) [-3.1629]	-0.0876(0.0114) [-7.6262]		
EI <sub>2</sub>			-0.0341(0.0101) [-3.3741]	-0.1566(0.0936) [-1.6731]
IQ	-0.1449(0.0265) [-5.4535]	-0.0794(0.0231) [-3.4253]	-0.0163(0.0018) [8.7263]	-0.0925(0.0435) [-2.126]
FDI	0.058(0.124) [0.4678]	0.0766(0.0186) [4.0978]	0.1574(0.0556) [2.8285]	0.1271(0.033) [3.8446]
FD	-0.0997(0.5558) [-0.1793]	-0.1062(0.0985) [-1.0784]	-0.0211(0.0058) [-3.633]	-0.1377(0.0963) [-1.4287]
ΔEE	-0.0415(0.3399)[-0.1223]	0.0462(0.0103) [4.4687]	-0.0523(0.0163)[-3.1979]	0.0533(0.052) [1.0238]
ΔEI	-0.0361(0.0912) [-0.3957]	-0.0292(0.0186) [-1.5703]	0.0468(0.0193) [2.4198]	0.0679(0.108) [0.6288]
ΔEI	0.0433(0.0068) [6.2981]	0.0299(0.0041) [7.1783]	-0.0063(0.0016) [-3.8157]	0.0076(0.0309) [0.2472]
ΔIQ	0.0975(0.0291) [3.3526]	0.0671(0.0169) [3.961]	0.0493(0.0236) [2.0828]	-0.0049(0.0301) [-0.1654]
ΔFDI	0.0322(0.0529) [0.6082]	-0.0233(0.0135) [-1.7189]	0.0518(0.0177) [2.9127]	0.019(0.0699) [0.2722]
ΔFD	-0.0846(0.0185) [-4.5581]	-0.1805(0.032) [-5.6346]	0.0211(0.012) [1.7612]	0.0023(0.002) [1.1529]
ECT(-1)	-0.3737(0.4373) [-0.8544]	-0.1846(0.0972) [-1.8982]	-0.0924(0.0466)[-1.9793]	-0.2616(0.7996)[-0.3272]
H-test	0.5541	0.6371	0.5521	0.2274

Note: the value in () represent standard effort and in [] denotes t-statistics.

Using the Panel Causality Tests developed by Dumitrescu and Hurlin (2012) [28], the direction of the association between environmental sustainability, energy efficiency, environmental innovation, institutional quality, foreign direct investment, and financial development was investigated. The findings of the panel causality test for carbon emission as an indicator of environmental sustainability in Panel A and ecological footprint as an indicator of environmental sustainability in Panel B are shown in Table 9. We focused on causation from explanatory elements to environmental sustainability. Multiple directional causalities have been established amongst study units, and we have chosen to analyze the directional effects of independent variables on

environmental sustainability. For panel A, the Study discovered a bidirectional causal link between environmental sustainability and energy efficiency, as well as between institutional quality and environmental sustainability. Moreover, environmental innovation, foreign direct investment, and financial growth contribute in a unidirectional manner to environmental sustainability. The feedback theory explains the causal link between energy efficiency, environmental sustainability, and institutional quality. In addition, environmental sustainability supports environmental innovation, economic expansion, and foreign direct investment unidirectionally.

**Table 9:** results of causality test: E.I. measured by the total number of patent

	ES	EE	EI	IQ	FDI	FD
<b>Panel –A: Environmental sustainability measured by CO<sub>2</sub></b>						
ES		(4.8618)*** [5.1243]	(6.1222)*** [6.4528]	1.543 [1.6263]	(5.0361)*** [5.308]	(3.6365)** [3.8329]
EE	(4.7959)*** [5.0549]		(6.017)*** [6.3419]	(4.1891)** [4.4153]	(5.5738)*** [5.8748]	(2.8671)** [3.0219]
EI	(2.4197)* [2.5504]	(4.1859)** [4.412]		(4.1987)** [4.4254]	1.8724 [1.9735]	(3.3889)** [3.5719]
IQ	(5.3623)*** [5.6519]	(3.5781)** [3.7713]	(3.272)** [3.4487]		(3.3921)** [3.5753]	(4.5387)** [4.7838]
FDI	(6.0541)*** [6.3811]	1.2306 [1.297]	(6.1615)*** [6.4942]	1.5589 [1.6431]		(6.1976)*** [6.5323]
FD	1.1976 [1.2623]	(3.0754)** [3.2415]	1.3039 [1.3743]	1.6014 [1.6879]	(2.8235)* [2.976]	
<b>Panel –B: environmental sustainability measured by Ecological footprint</b>						
ES		(2.6068)* [2.7475]	(2.0106)* [2.1192]	(5.984)*** [6.3071]	0.8097 [0.8535]	(5.0116)*** [5.2823]
EE	1.3145 [1.3855]		(2.7619)* [2.9111]	(2.4112)* [2.5414]	(6.2614)*** [6.5995]	(3.1445)** [3.3143]
EI	0.8554 [0.9016]	(3.2146)** [3.3882]		(2.0648)* [2.1763]	(3.1445)** [3.3143]	(3.9362)** [4.1487]
IQ	1.0106 [1.0652]	1.1615 [1.2242]	(4.6121)** [4.8611]		(5.6896)*** [5.9969]	(4.4452)** [4.6853]
FDI	(5.2656)*** [5.55]	1.8682 [1.9691]	(3.7938)** [3.9987]	(3.7874)** [3.9919]		(5.7577)*** [6.0686]
FD	(3.0882)** [3.2549]	(2.6556)* [2.799]	1.8427 [1.9422]	(4.2242)** [4.4523]	(3.8065)** [4.0121]	

**Conclusion**

This study examines the role of energy efficiency, environmental innovation, and institutional quality in attaining environmental sustainability in the Southeast Asian economy between 1980 and 2020. Several econometric techniques were used to examine the empirical relationship, and the following are the key findings of the Study: First, The statistical significance of the test's findings for cross-sectional dependence suggests that the null hypothesis of cross-sectional independence should be rejected. Consequently, it may be stated that these research units share vigor. In addition, the slope of the homogeneity test suggests that the variables chosen for the Study have distinct features. Second, The sequence of variable integration has been exposed with the deployment of the panel unit root test. The

conventional unit root test has shown that variables are integrated in mixed order, indicating that variables are stationary either at a level or after first differences but not after second differences. In addition, the research employs a unit root test with cross-sectional features, and recorded variables are stationary after the initial difference. Third, using a panel cointegration test, the long-run cointegration between energy efficiency, environmental innovation, institutional quality, and environmental sustainability was evaluated (2007). Refers to the test statistics for panel cointegration, which demonstrate the empirical relationship's long-run connection. Long-term co-motion effects may be seen on both sides, with environmental quality enhancing energy efficiency and economic innovation. Any negative environmental innovation, improvement in energy



efficiency, or institutional development may have environmental repercussions.

Consequently, policymakers must address all interdependent aspects of environmental cost management. Fourth refers to the magnitudes of Environmental Sustainability objective factors. Environmental innovation, energy efficiency, and institutional quality have boosted efforts to preserve ecological balance by reducing carbon emissions and supporting ecological development, according to the Study. Environmentally advanced technology growth in the economy helps manage environmental costs by lowering carbon emissions and ecological degradation, as demonstrated by the Study. Similar to the results of Lin and Zhu (2019)<sup>[51]</sup>, Mensah *et al.* (2018)<sup>[57]</sup>, and Ali *et al.* (2021)<sup>[9]</sup>; (Anselme & Qamruzzaman, 2022)<sup>[13]</sup>.

Clean energy integration enables industrial output with less ecological destruction, as evidenced by the correlation between energy efficiency and environmental development. This is because energy efficiency promotes environmental development by reducing ecological imbalance through reducing carbon emissions. Energy efficiency looks to be a particularly appealing option for decreasing energy-related environmental and health consequences. In principle, if we can maintain service levels while using less energy, we can lessen the impact on our infrastructure, our pockets, our health, and the environment.

#### Data Availability Statement

The original contributions presented in the Study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors

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