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# The role of renewable energy in the energy–growth–emission nexus in the ASEAN region

Thao Tran[1], Hung Bui[1], Anh The Vo[2] and Duc Hong Vo[2*]

**Abstract**

**Background** The Association of Southeast Asian Nations (ASEAN) relies mainly on fossil fuels in their energy supply, leading to higher $CO_2$ emissions, pollution, and further environmental degradation. This paper uses the panel vector autoregressive and the Granger non-causality test in the heterogeneous panels, together with long-run estimation techniques, to examine the dynamic link among energy consumption, economic growth, and carbon emissions with the focus on renewable energy for the ASEAN countries in the past three decades.

**Results** The findings from this paper indicate that carbon emissions are associated with energy consumption. In contrast, renewable energy usage reduces $CO_2$ emissions, improving environmental quality. Economic growth is associated with increased energy consumption and carbon emissions in the ASEAN countries. The findings also indicate that the effects of energy consumption on economic growth are more significant than those of renewable energy in ASEAN. When considered together, these findings form a vicious circle regarding the energy–growth–emission nexus for the ASEAN economies. In addition, a bidirectional Granger causality among energy consumption, economic growth, $CO_2$ emissions and renewable energy usage is confirmed.

**Conclusions** Renewable energy has emerged as an important viable option for the ASEAN nations to achieve their dual objectives of enhanced economic growth, reduced $CO_2$ emission, leading to improved environmental quality.

**Keywords** Renewable energy, Energy consumption, Economic growth, Carbon emissions, ASEAN

## Background

Countries in the Association of Southeast Asian Nations (ASEAN) region have achieved significant economic growth and social transformation in the past three decades. Together with the increased population, the overall energy supply in the region increased by approximately 80 per cent between 2000 and 2020. During this period, coal consumption climbed by six, and its proportion of the overall energy supply increased from 8 per cent to 26 per cent [1]. Oil consumption has surged by more than 40 per cent since 2000, despite its proportion of the overall energy supply decreasing from 40 per cent to 32 per cent. Natural gas use increased by more than 80 per cent between 2000 and 2020, and it now accounts for almost 20 per cent of overall energy consumption [1, 2]. Specifically, the power and industrial sectors account for 70 per cent of total natural gas use today. Traditional biomass usage as a cooking fuel has steadily declined over the last 20 years, with overall use halving. During the period, the energy provided by current renewable types more than quadrupled. However, solar PV and wind energy have grown fast in recent years. Modern bioenergy, geothermal energy, and hydropower account for more than 98 per cent of all modern renewable energy in Southeast Asia today. Geothermal resources are mostly

*Correspondence:
Duc Hong Vo
duc.vhong@ou.edu.vn
[1] International School of Business, The University of Economics Ho Chi Minh City Vietnam, 59C Nguyen Dinh Chieu Street, District 3, Ho Chi Minh City, Vietnam
[2] Research Centre in Business, Economics and Resources, Ho Chi Minh City Open University Vietnam, 97 Vo Van Tan Street, District 3, Ho Chi Minh City, Vietnam

found in Indonesia and the Philippines; Cambodia, Lao PDR, and Myanmar have continued to develop domestic hydropower resources, leveraging their steep terrains and heavy precipitation [1] (Fig. 1).

With global worries about climate change and carbon lock-in growing, Southeast Asia has a unique possibility to progress its economy and global leadership by building a regional low-carbon electrical infrastructure. The ASEAN nations have vast solar energy resources and excellent manufacturing capabilities for battery energy storage and electric cars, making them ideal candidates to lead the worldwide transition to clean energy [2]. Following the Paris Agreement, several ASEAN nations have amended their power development plans to incorporate aggressive pledges to decarbonize the power sector. ASEAN member nations have promised to produce at least 23 per cent of their power from renewable sources by 2025. Vietnam has authorized over 11 gigatons (GW) of new wind projects, while Thailand is creating 2.7 GW of floating solar [2]. Following negotiations at the COP26 in 2021, five major Southeast Asian countries set carbon neutrality goals for 2050 and plans to phase out coal. These initiatives are designed to give ASEAN nations the tools to increase and divert investments toward renewables and innovative energy technology [3, 4].

The interaction among energy consumption, economic growth, and carbon emissions in different parts of the world has attracted significant attention from policymakers, practitioners, and academics in the past three decades. This concern is relevant in the ASEAN region. Over previous decades, the ASEAN region has achieved impressive economic growth and social transformation. Supporting economic growth requires energy consumption, which relies heavily on fossil fuels in the ASEAN countries. As a result, the energy demand in the region is expected to grow as much as 2.3 times (or 230 per cent) over the long-term projections to 2040. Unlike fossil fuels, renewable energy releases less $CO_2$ emissions, thus mitigating the negative impact on the environment. Renewable energy from solar and wind is generally considered unlimited resources. Renewable energy ensures increased energy security, sustainable economic growth, and improved environmental quality [5]. The ASEAN countries have considered that renewable energy and energy efficiency bring a potential benefit to reduce the reliance on fossil fuels, ensuring targeted economic growth and achieving energy security, affordability, and sustainability.

Various studies have examined the inter-relationship between economic growth, energy consumption and renewable energy in the ASEAN region [6–8]. However, the focus of these previous studies is different. Saboori and Sulaiman [6] examine the cointegration and causal relationship between economic growth, carbon emissions, and energy consumption for selected ASEAN countries from 1971 to 2009 using the autoregressive distributed lag (ARDL) methodology and Granger causality test based on vector error-correction model (VECM). However, renewable—a key pillar in energy policy for the ASEAN region has been ignored in their analysis. Vo et al. [7] examine the dynamic link between $CO_2$ emissions, energy consumption and renewable energy consumption. However, their study tests the validity of the region's long-run environmental Kuznets curve (EKC). Vo and Vo [8], focusing on renewable energy and population, examine a causal link between them. Their study

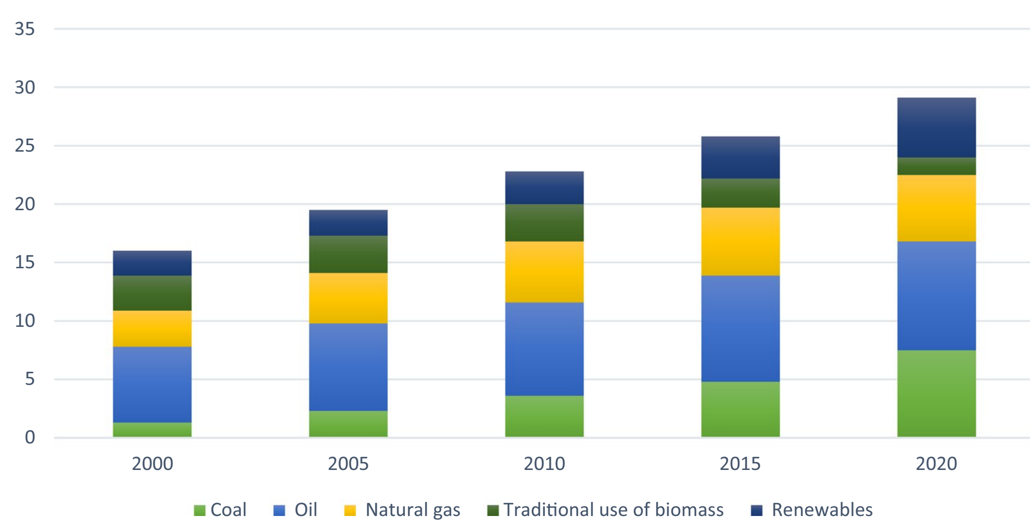


**Fig. 1** Total primary energy supply by fuel in Southeast Asia, 2000–2020. Source: The International Energy Agency (IEA) [1]

appears to focus more exclusively on the region's population growth. The findings from these studies have motivated us to conduct an empirical analysis with a focus on the role of renewable energy in the energy–growth–emission nexus, in the long run, using state-of-the-art estimation techniques for the ASEAN region. Anwar et al. [9] examine the moderating role of renewable and non-renewable energy in the environment–income nexus for ASEAN countries using the novel method of moments quantile regression for ASEAN countries. Their findings confirm that non-renewable energy consumption stimulates carbon emissions across all quantiles, and renewable energy consumption decreases $CO_2$ emissions across all quantiles. Yan and Uprasen [10] investigated the carbon neutrality potential of the ASEAN-5 countries with a focus on the asymmetric effects of income inequality on renewable energy consumption using a nonlinear panel autoregressive distributed lag (ARDL) model from 1990 to 2015. They found that alleviating income inequality promotes renewable energy consumption in the long run and vice versa. In addition, their findings reveal that the positive shock (worsening of inequality) of income inequality generates a larger impact on renewable energy consumption than the result from the negative shock (improvement of inequality).

The contributions of our paper to the existing literature on the energy–growth–emission nexus, particularly for the ASEAN region, are twofold. *First*, previous studies confirm the vital role of renewable energy in boosting economic growth and reducing carbon emissions. However, those studies mainly focus on the EU countries and the American regions. The ASEAN region has largely been underexamined in the current literature. In addition, empirical studies focusing on the ASEAN region tend to examine the relationship between carbon emissions, energy consumption, and economic growth. The role of renewable energy has largely been underexamined. *Second*, governments of the ASEAN countries such as Indonesia, Thailand and Vietnam have made strong commitments to relying on renewable energy usage in the national energy policy to reduce pollution, leading to improved environmental quality. As such, understanding the important role of renewable energy in the energy–growth–emissions nexus, particularly in the long run, is essential. Findings from this study provide additional evidence to support the governments in the ASEAN region to formulate and implement policies and strategies for recognizing the important role of renewable energy in the national energy strategy.

The paper is structured as follows. Following this background, the next section discusses relevant theories, empirical studies, and the causal relationship between energy consumption, economic growth, and $CO_2$ emission. The research methodology is then presented. The next section presents empirical results and discussions of these findings. The conclusions are then discussed in the last section of the paper.

## Literature review

### The environmental Kuznets curve hypothesis

The relationship between economic growth and environmental degradation has recently gained significant attention among scholars, focusing on testing the environmental Kuznets curve (EKC) hypothesis. The hypothesis considers that economic growth initially leads to environmental damage and improves environmental quality after a specific threshold of economic growth. However, the validity of the hypothesis has been challenged.

Saboori et al. [11] used the ARDL to investigate the EKC hypothesis for Malaysia from 1980 to 2008. The study confirms an inverted U-shaped relationship between income and $CO_2$ emission in the long run. Heidari et al. [12] also examine the relationship between economic growth and $CO_2$ emission in the five ASEAN countries (including Indonesia, Malaysia, the Philippines, Singapore, and Thailand) using panel smooth transition regression (PSTR). The authors conclude a nonlinear relationship between $CO_2$ emissions, energy consumption, and economic growth. Furthermore, the study finds that $CO_2$ emissions increased with economic growth and decreased if the per capita GDP was above USD 4686. Aslan et al. [13] used the bootstrap rolling window estimation of the VAR model for the US from 1966 to 2013. Their findings confirm that the effect of economic growth on $CO_2$ emissions increased from 1982 to 1996 and decreased from 1996 to 2013. As such, their findings confirm the validity of the U-shaped EKC hypothesis.

On the other hand, other empirical studies provide evidence against the EKC hypothesis. For example, Al-Mulali et al. [14] employ the ARDL to investigate the causal relationship between $CO_2$ emission and Vietnam's economic growth from 1981 to 2011. They argue that economic growth is positively related to pollution in the short and long run, suggesting rejecting the EKC hypothesis. While previous studies that find evidence for the ECK hypothesis assume a quadratic relationship between economic growth and $CO_2$ emission, Fakih and Marrouch [15] show that a non-parametric model might confirm a positive relationship between $CO_2$ emission and GDP without a turning point. The study uses data from the Middle East and North African countries from 1980 to 2010 and finds evidence to reject the ECK hypothesis. Zambrano-Monserrate et al. [16] use an ARDL framework to compare the long-run and short-run elasticities of $CO_2$ emission to economic growth in Peru from 1980 to 2011. The findings show that the impact of economic growth is positive and more robust in the long run than in the short run, rejecting the validity of the EKC hypothesis.

In other studies, mixed evidence is found regarding the EKC hypothesis. For example, Saboori and Sulaiman [6] investigated the EKC hypothesis for selected countries in the Association of Southeast Asian Nations (ASEAN) over the period 1971–2009 using the autoregressive distributed lag (ARDL) approach and Granger causality test based on vector error-correction model (VECM). The study confirms an inverted U-shaped relationship between income and $CO_2$ emissions when energy consumption is disaggregated based on various sources such as gas, oil, coal, and electricity. However, the evidence for the EKC hypothesis can only be found in Singapore and Thailand, while the results for Indonesia, Malaysia, and the Philippines do not support the hypothesis. The author argues that the outcomes are expected because the selected countries have different economic development stages. Similarly, Le and Quah [17] examine the $CO_2$ emission–growth nexus for 14 selected countries in the Asia Pacific region from 1984 to 2012 using the fully modified OLS estimators (FMOLS). The study finds evidence for the ECK hypothesis for the high-income economies (including Hong Kong and South Korea) and evidence against the inverted U-shaped between $CO_2$ emission and economic growth for middle-income countries (Thailand, China, Indonesia, and Pakistan). Malaysia and the Philippines are the only middle-income countries whose evidence supports the ECK hypothesis.

Some studies even support an N-shaped relationship between $CO_2$ emission and economic growth. Churchill et al. [18] argue that investigating panel data and individual countries may yield different outcomes. The authors find supportive evidence for the ECK hypothesis using the mean group estimators for the panel data. However, only 9 of 20 OECD countries confirm the ECK hypothesis when the authors investigate individual countries. Among these nine countries, six of them show a second turning point. The resurging of $CO_2$ emission, when income reaches the second turning point suggests an N-shaped rather than a U-shaped relationship between $CO_2$ emission and economic growth. Shahbaz, Haouas, and Hoang [19] test the possibility of an N-shaped curve using the cube term of economic growth, ARDL bound testing, and VECM Granger causality test for Vietnam over the 1974–2016 period. The existence of the N-shaped curve is confirmed in the long run but not in the short run.

### The causality relationship among energy consumption, economic growth, carbon emission, and renewable energy usage

Ang [22] investigates the relationship between economic growth, $CO_2$ emission, and energy use in Malaysia from 1971 to 1999 using ECM-based causality tests. The author finds a unidirectional causality from economic growth to energy consumption. The study also finds weak evidence for the feedback effect in the long run. Azlina and Mustapha [23] present a unidirectional causality from $CO_2$ emission to energy consumption in Malaysia from 1970 to 2010. The results are robust for both the long run and short run. Hwang and Yoo [24] use the ECM to test the causality between $CO_2$ emission and energy consumption in Indonesia. They show that there is a bidirectional causality between these variables. Finally, Saboori and Sulaiman [6] employed the VECM to detect the causality link between $CO_2$ emission and energy consumption for five ASEAN countries (including Indonesia, Malaysia, the Philippines, Singapore, and Thailand) from 1971 to 2009. Long-run causality from energy consumption to $CO_2$ emission is found in all selected ASEAN countries except Indonesia. In contrast, the short-run causality is found in all except Thailand at a 5 per cent significance level. They conclude that a bidirectional causality between these variables is found in the short run for only Indonesia, Thailand, and Singapore. In contrast, the causality for all these five selected countries is found in the long run.

Shahzad et al. [25] confirm an inverted U-shaped relationship between energy consumption and $CO_2$ emission in Pakistan from 1971 to 2011, using an ARDL bound tests framework. The authors capture the threshold effect of energy consumption where the impact of energy consumption on $CO_2$ emission is positive below a certain threshold and becomes negative when energy use passes a turning point. When energy consumption is below the threshold, the economy expands and consumes more energy, leading to more $CO_2$ emissions (scale effect). On the other hand, when economic development and energy consumption are above the threshold, more efficient technologies are applied, leading to less pollution (technology effect).

The sources of energy consumption play an essential role in the relationship between energy consumption and $CO_2$ emission. Al-Mulali et al. [14] find a significantly positive relationship between fossil fuel energy consumption and $CO_2$ emission in Vietnam. The authors show that renewable energy consumption and $CO_2$ emission are negatively correlated. Similar results are found by [26] for Pakistan from 1970 to 2016, using an ARDL approach. In contrast, Raza and Shah [27] found a significantly negative link between $CO_2$ emission and renewable energy for the G7 countries (including Canada, France, Germany, Italy, Japan, the UK, and the US) for the 1991–2016 period using the DOLS, FMOLS, and the fixed effects technique. Solarin, Al-Mulali, and Ozturk [28] confirm a negative impact of hydroelectricity on $CO_2$ emission in China and India from 1965 to 2013, utilizing the ARDL bound testing approach.

Research also emphasizes the causal relationship between $CO_2$ emission and economic growth. A seminal work is by [22], who found causality from $CO_2$ emission to economic growth in the long run, without feedback effects, for Malaysia from 1971 to 1999. After that, various studies have been conducted to determine how $CO_2$ emission and economic growth interact. Bekhet and Othman [29] show a bidirectional causality relationship between these two variables in the short-run in Malaysia over the 1971–2015 period using the VECM Granger causality test. Chandran and Tang [30] conducted a comprehensive investigation to examine the effect of income on $CO_2$ emission for each of the 5 ASEAN countries—Malaysia, the Philippines, Singapore, Thailand, and Indonesia. Their findings found a bidirectional causality between economic growth and $CO_2$ emission for Indonesia and Thailand in the long run. A unidirectional causality from economic growth to $CO_2$ emission is also found in the short run. Moreover, they confirm a unidirectional relationship is from economic growth to $CO_2$ emission for Malaysia and the reversed effect for the Philippines in the short run. Singapore has a bidirectional causality between economic growth and $CO_2$ emission. Also, within the VECM framework, Saboori and Sulaiman [6] find evidence for long-run bidirectional Granger causality relationships between economic growth and $CO_2$ emission for Indonesia, Malaysia, and the Philippines. The same study found short-run bidirectional relationships for Indonesia, Singapore, and Thailand. Sulaiman and Abdul-Rahim [31] confirm the important role of economic growth and energy consumption in increasing $CO_2$ emission in Malaysia from 1975 to 2015, employing the ARDL approach and VECM Granger causality framework.

## Method

Our main objective is to investigate the important role of renewable energy in the energy–growth–emission nexus in the long run and their causality relationship for the ASEAN countries in the past three decades. Previous studies have been considered in forming our regression model [21, 32–44]. Our regression specification is expressed as follows:

$$\begin{aligned}\mathrm{LnPCCO}_{2\mathrm{it}} = {} & \alpha_0 + \alpha_1 \mathrm{LnPCGDPR}_{\mathrm{it}} + \alpha_2 \mathrm{lnPCGDPR}^2_{\mathrm{it}} \\ & + \alpha_3 \mathrm{lnPCEC}_{\mathrm{it}} + \alpha_4 \mathrm{LnPCREC}_{\mathrm{it}} \\ & + \alpha_5 \mathrm{LnPOP}_{\mathrm{it}} + \varepsilon_{\mathrm{it}},\end{aligned} \tag{1}$$

where i and t represent the number of the country and the period, respectively. $PCCO_{2it}$ represents the per capita $CO_2$ emissions and $PCGDPR_{it}$ and $PCGDPR^2_{it}$ are the real per capita gross domestic product (GDP) and its squared term. $PCEC_{it}$ denotes the per capita energy consumption. $PCREC_{it}$ represents per capita renewable energy usage. $POP_{it}$ is the population. Finally, $\varepsilon_{it}$ is the error term, and Ln denotes the nature of the logarithm. All variables are expressed in the form of the logarithm. As such, the estimated coefficients can be interpreted in terms of the elasticity, showing the per cent of $CO_2$ emissions per capita changes with a 1 per cent change in the independent variables. The descriptive statistics for the variables used in our analysis are presented in Table 1 below.

Table 2 presents the correlation matrix between variables used in our analysis. The results indicate a weak correlation between real per capita GDP, the square of real per capita GDP, and per capita $CO_2$ emissions at the first differences. The estimated approach used in this study relies on the first differences. As such, multicollinearity does not matter.

## Results

We use the panel unit root test by [45], including the inverse Chi-square, inverse normal, inverse logit and modified inverse Chi-square test, to examine the stationarity of the variables in our sample. The results are presented in Table 3, indicating that all variables are integrated I(1).

**Table 1** The descriptive statistics

| Variable | Obs | Mean | Std. Dev | Min | Max |
|---|---|---|---|---|---|
| $LnPCCO_2$ | 149 | 0.51 | 1.31 | − 2.29 | 2.89 |
| LnPCGDPR | 149 | 7.97 | 1.38 | 5.26 | 10.86 |
| $LnPCGDPR^2$ | 149 | 65.43 | 22.69 | 27.71 | 118.02 |
| LnEC | 149 | 6.83 | 0.97 | 5.54 | 8.91 |
| LnREC | 149 | 5.07 | 0.84 | 2.00 | 6.16 |
| LnPOP | 149 | 17.66 | 1.16 | 14.93 | 19.43 |

$PCCO_2$: per capita $CO_2$ emissions; PCGDPR: per capita real GDP; $PCGDPR^2$: the square of per capita real GDP; POP: population; REC: renewable energy consumption; EC: energy consumption. "Ln" represents the logarithm. Fossil fuels include oil, coal, and gas. Renewable energy includes nuclear, hydro, wind, solar, geothermal, biomass in power and other renewable sources

**Table 2** Correlation matrix

| | $\Delta LnPCCO_2$ | ΔLnPCGDPR | $\Delta LnPCGDPR^2$ | ΔLnEC | ΔLnREC | ΔLnPOP |
|---|---|---|---|---|---|---|
| $\Delta LnPCCO_2$ | 1.00 | | | | | |
| ΔLnPCGDPR | 0.36 | 1.00 | | | | |
| $\Delta LnPCGDPR^2$ | 0.37 | 0.98 | 1.00 | | | |
| ΔLnEC | 0.43 | 0.38 | 0.44 | 1.00 | | |
| ΔLnREC | 0.08 | 0.19 | 0.21 | 0.50 | 1.00 | |
| ΔLnPOP | − 0.05 | − 0.27 | − 0.22 | − 0.07 | − 0.29 | 1 |

$PCCO_2$: per capita $CO_2$ emissions; PCGDPR: per capita real GDP; $PCGDPR^2$: the square of per capita real GDP; POP: population; REC: renewable energy consumption; EC: energy consumption. "Δ" denotes the variable in terms of the first differences. Fossil fuels include oil, coal, and gas. Renewable energy includes nuclear, hydro, wind, solar, geothermal, biomass in power and other renewable sources

**Table 3** The empirical results for the unit-root tests based on Choi [45]

| | Inverse Chi-squared | Inverse normal | Inverse logit t | Modified inverse Chi-squared |
|---|---|---|---|---|
| | P | Z | L* | Pm |
| The level | | | | |
| $LnPCCO_2$ | 10.50 | 1.00 | 1.07 | − 0.97 |
| LnPCGDPR | 5.17 | 3.08 | 3.26 | − 1.91 |
| $LnPCGDPR^2$ | 2.57 | 3.79 | 3.94 | − 2.37 |
| LnPOP[a] | 37.41*** | − 2.81*** | − 3.13*** | − 3.78*** |
| LnREC | 17.89 | 0.19 | 0.38 | 0.33 |
| LnEC | 21.46 | − 0.30 | − 0.37 | 0.96 |
| The first difference | | | | |
| $\Delta PCCO_2$ | 27.69** | − 2.43*** | − 2.30** | 2.07** |
| ΔPCGDPR | 27.52** | − 2.23** | − 2.16** | 2.04** |
| $\Delta PCGDPR^2$ | 29.31** | − 2.42*** | − 2.37** | 2.35*** |
| ΔPOP[a] | 23.78* | − 1.56* | − 1.57* | − 1.37* |
| ΔPCREC | 44.52*** | − 3.83*** | − 4.07*** | 5.04*** |
| ΔPCEC | 33.88*** | − 2.67*** | − 2.76*** | 3.16*** |

***, ** and * denote the rejection of containing unit roots at the significance level of 1, 5 and 10 per cent. The test includes an intercept and a trend

$PCCO_2$: per capita $CO_2$ emissions; PCGDPR: per capita real GDP; $PCGDPR^2$: the square of per capita real GDP; POP: population; REC: renewable energy consumption; EC: energy consumption. "Ln" represents the logarithm

**Table 4** Cointegration tests

| **Westerlund [46]** | | | | |
|---|---|---|---|---|
| **Statistics** | **Gt** | **Ga** | **Pt** | **Pa** |
| Z-value | 0.58 | 4.64 | − 0.96 | 3.40 |
| **Pedroni [47]** | | | | |
| **Statistics** | **v** | **rho** | **t** | **ADF** |
| Panel | − 0.94 | 0.42 | − 3.10*** | − 1.41 |
| Group | | 1.42 | − 3.22*** | − 1.52 |

*** denotes the rejection of containing unit roots at the significance level of 1 per cent

**Table 5** PVAR's optimal lags length

| lag | CD | J-statistics | p-value | MBIC | MAIC | MQIC |
|---|---|---|---|---|---|---|
| 1 | 0.86 | 103.83 | 0.38 | − 379.00 | − 96.17 | − 211.07 |
| 2 | 0.95 | 84.89 | 0.20 | − 277.24 | − 65.11 | − 151.29 |
| 3 | 0.96 | 57.15 | 0.23 | − 184.26 | − 42.85 | − 100.30 |
| 4 | 0.95 | 30.65 | 0.20 | − 90.05 | − 19.35 | 48.07 |

J statistic and corresponding p-value is based on [48], and other moment model selection criteria (MMSC) are developed by [49]. Bayesian information criterion (MBIC), MMSC-Akaike information criterion (MAIC), and MMSC-Hannan and Quinn information criterion (MQIC)

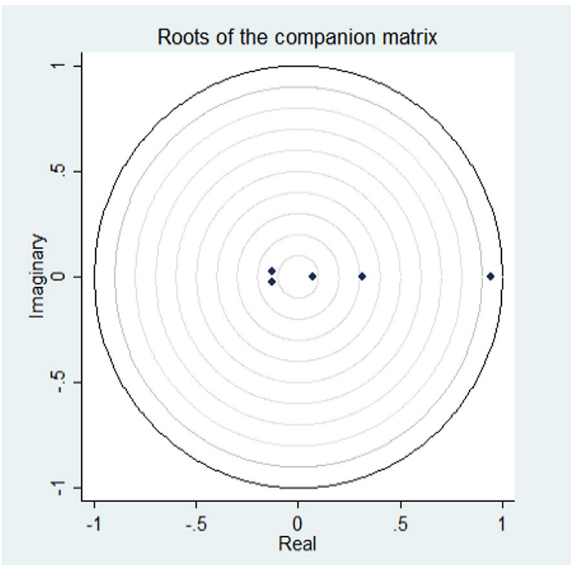


**Fig. 2** Roots of the companion matrix. The PVAR models are stable as all the AR roots lie inside the unit circle, indicating variables are covariance stationary

The cointegration test is now performed to examine a long-run relationship. We use two tests Westerlund [46] and Pedroni [47] proposed. Results are reported in Table 4. No cointegration relationship is found among the selected variables. Thus, we conclude that no long-run relationship exists among the variables of interest.

All variables used in our model are I(1). We now examine the dynamic effects among these variables using the PVAR framework. The procedure begins with the selection of optimal lag length. In Table 5, three criteria of MBIC, MAIC and MQIC indicate that the first lag is optimal consistently. We use one lag for all variables in the PVAR model.

Figure 2 presents the plotted eigenvalues within the unit circles, implying that the stability of the PVAR estimation is valid. In addition, Table 6 presents our empirical results on variance decomposition.

Figure 3 from a to d illustrates a response of a shock of $CO_2$ emissions, renewable energy consumption, energy consumption, and economic growth to the shock of itself and other variables. For example, Fig. 3a illustrates that $CO_2$ emissions respond positively to a shock of energy consumption and are negatively affected by a shock of renewable energy consumption and economic growth. This means increased energy usage goes hand in hand with $CO_2$ emissions.

Figure 3b shows that its shock to other variables and from other variables is statistically significant for the response of renewable energy consumption.

**Table 6** Variance decomposition of LnPCCO$_2$

| Period | ΔPCCO$_2$ | ΔPCGDPR | ΔPOP | ΔPCREC | ΔPCEC |
|---|---|---|---|---|---|
| ΔPCCO$_2$ | | | | | |
| 2 | 99.28 | 0.35 | 0.05 | 0.08 | 0.25 |
| 4 | 98.52 | 0.44 | 0.59 | 0.09 | 0.36 |
| 8 | 97.54 | 0.51 | 1.45 | 0.11 | 0.39 |
| 12 | 96.94 | 0.56 | 1.99 | 0.12 | 0.40 |
| ΔPCGDPR | | | | | |
| 2 | 11.04 | 49.77 | 38.64 | 0.06 | 0.50 |
| 4 | 19.00 | 30.21 | 48.99 | 0.76 | 1.03 |
| 8 | 22.68 | 20.67 | 54.49 | 0.91 | 1.24 |
| 12 | 23.82 | 17.69 | 56.22 | 0.96 | 1.31 |
| ΔPOP | | | | | |
| 2 | 11.64 | 2.33 | 84.38 | 1.39 | 0.27 |
| 4 | 18.58 | 3.68 | 75.86 | 1.23 | 0.65 |
| 8 | 22.38 | 4.46 | 70.97 | 1.19 | 1.00 |
| 12 | 23.58 | 4.71 | 69.42 | 1.18 | 1.11 |
| ΔPCREC | | | | | |
| 2 | 2.91 | 0.04 | 6.56 | 88.90 | 1.60 |
| 4 | 4.55 | 0.31 | 10.99 | 82.65 | 1.49 |
| 8 | 6.78 | 0.81 | 15.95 | 74.97 | 1.49 |
| 12 | 8.02 | 1.09 | 18.64 | 70.76 | 1.49 |
| ΔPCEC | | | | | |
| 2 | 8.57 | 2.93 | 4.98 | 36.86 | 46.66 |
| 4 | 10.63 | 3.32 | 9.49 | 33.63 | 42.93 |
| 8 | 12.59 | 3.59 | 15.25 | 30.11 | 38.47 |
| 12 | 13.61 | 3.73 | 18.34 | 28.23 | 36.09 |

PCCO$_2$: per capita $CO_2$ emissions; PCGDPR: per capita real GDP; PCGDPR$^2$: the square of per capita real GDP; POP: population; REC: renewable energyconsumption; EC: energy consumption. Ln represents the logarithm. Fossil fuels include oil, coal, and gas. Renewable energy includes nuclear, hydro, wind,solar, geothermal, biomass in power and other renewable sources

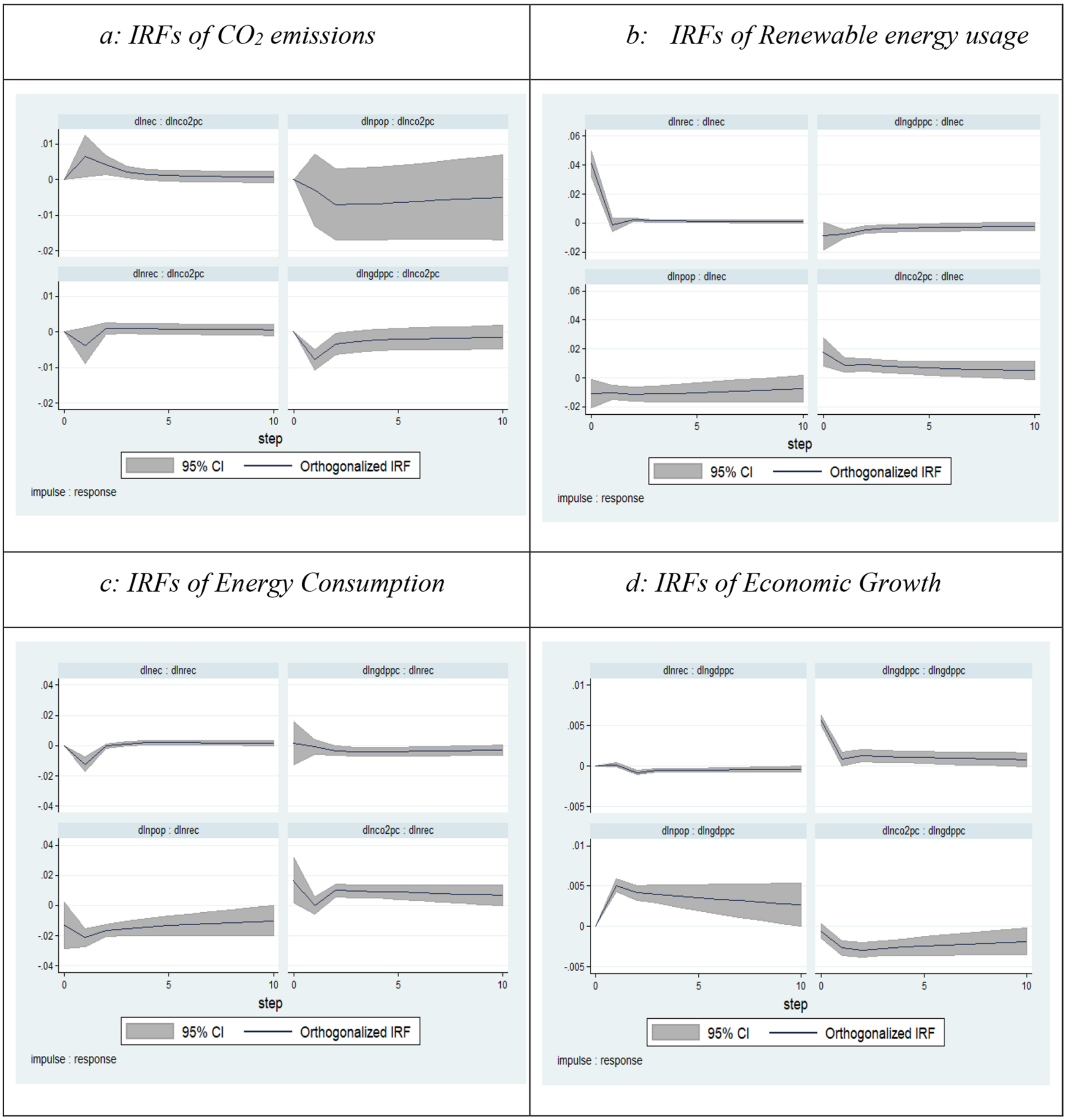


**Fig. 3** The results of impulse response functions (IRFs). The responses of the selected variables are represented by the solid line, while the two standard error bands are covered with the two shaped lines. The response is statistically significant when the bands do not cross the zero line

Specifically, renewable energy responds positively to a shock from $CO_2$ emissions and adverse to a shock from economic growth and population growth. As shown in Fig. 3c, the energy consumption response revealed that the responsive patterns are entirely different regarding the energy consumption response. Energy consumption experiences a significantly negative response to renewable energy consumption and population growth shocks. A shock of economic growth affects energy consumption, while $CO_2$ emissions are observed to be positive and statistically significant. As shown in Fig. 3d, economic growth has a statistically positive response to population growth. It responds negatively to a shock of energy consumption rather than

**Table 7** Results from Pesaran's test for cross-sectional dependence

| Variables | CD test | p-value |
|---|---|---|
| $CO_2$ emissions per capita | 14.22*** | 0.000 |
| GDP per capita | 18.93*** | 0.000 |
| Renewable energy usage | 4.50*** | 0.000 |
| Energy consumption | 13.10*** | 0.000 |
| Population | 19.26*** | 0.000 |

All variables are natural logarithms. The symbol *** denotes the significance at the 1 per cent level. CD test represents Pesaran's test statistics for cross-sectional dependence with the null hypothesis of cross-sectional independence

renewable energy consumption. This finding indicates that the impact of energy consumption on economic growth seems to overtake that of renewable energy.

Table 7 presents our results regarding the forecast error variance decomposition, which provides us with the degree of the responses of one variable to the other remaining variables. We find that a change in economic growth in the ASEAN countries significantly causes variations in $CO_2$ emissions. Particularly, economic growth explains approximately 19 per cent of the variation in $CO_2$ emission after four periods. This degree reaches approximately 24 per cent after 12 years. Interestingly, our results indicate that renewable energy contributes approximately 8 per cent and 1 per cent to the variation of carbon emissions and economic growth. All these findings highlight the marginal contributions of renewable energy in supporting economic growth in the ASEAN countries. Findings also indicate that renewable energy usage contributes approximately 8 per cent to the variation of carbon emissions.

Our study also uses two long-run estimation techniques, including the fully modified OLS (FMOLS) and the dynamic OLS (DOLS), to investigate the effects of renewable energy on carbon emissions in the long run for the ASEAN countries. However, before these estimate techniques are implemented, we have conducted the preliminary tests, including the cross-sectional dependence and the slope homogeneity tests, to ensure that using the FMOLS and the DOLS techniques is appropriate for our analysis.

After the stationarity test is conducted, as presented in Table 2 above, the next step is to examine the cross-sectional dependence in the sample used in our analysis. Table 7 below presents our empirical findings regarding this test. Variables used in our analysis are highly significant at a 1 per cent level. These results confirm the cross-sectional dependence among the variables used in our analysis. These findings also confirm that the residuals are auto-correlated. Based on these findings, using the FMOLS and the DOLS techniques is appropriate for our analysis.

**Table 8** Results from tests for slope homogeneity and cointegration

| Test | Slope homogeneity | | Westerlund cointegration |
|---|---|---|---|
| | Delta | Adj. delta | Variance ratio |
| Statistics | 12.157***<br>(0.000) | 13.945***<br>(0.000) | − 1.789**<br>(0.037) |

The symbol *** and ** denotes the significance at 1 per cent and 5 per cent, respectively. The null hypothesis for slope homogeneity assumes strict cross-sectional independence. The null hypothesis for cointegration assumes no cointegration

The next step to support the use of the long-term estimation techniques, including the FMOLS and the DOLS, is to investigate the slope homogeneity and a long-run relationship among variables using Pesaran and Yamagata [50] test (the slope homogeneity) and the Westerlund and Edgerton [51] test (for the cointegration test). Empirical results from these two tests are presented in Table 8 below. We find that slope heterogeneity and long-run cointegration exist in the sample used in our analysis. In addition, we also find that a long-run relationship among the variables also exists in our analysis. These findings reconfirm our view that using the FMOLS and the DOLS techniques is appropriate for our analysis.

Table 9 presents the empirical results on the long-run effects of renewable energy and economic growth on carbon emissions in the ASEAN countries.

**Table 9** The long-run effects of renewable energy and economic growth on carbon emissions in the ASEAN countries

| | FMOLS | DOLS |
|---|---|---|
| | $CO_2$ emissions per capita | $CO_2$ emissions per capita |
| GDP per capita | 0.883*** | 0.875*** |
| | (0.073) | (0.088) |
| Renewable energy | − 0.724*** | − 0.703*** |
| | (0.091) | (0.112) |
| Energy consumption | − 1.062*** | − 1.020*** |
| | (0.177) | (0.215) |
| Population | 0.377*** | 0.364*** |
| | (0.064) | (0.078) |
| Constant | − 7.052*** | − 6.983*** |
| | (0.903) | (1.099) |
| Observations | 149 | 147 |
| Adjusted $R^2$ | 0.756 | 0.955 |

All variables are in the form of natural logarithms. FMOLS stands for fully modified OLS; DOLS stands for dynamic OLS. Standard errors are reported in parentheses. Symbol *** represents significant level at 1 per cent

**Table 10** Empirical results from the Granger causality tests

| Null hypothesis | Chi2-Statistic | Prob |
|---|---|---|
| ΔPCGDPR does not Granger-cause $ΔPCCO_2$ | 45.48 | 0.00 |
| ΔPOP does not Granger-cause $ΔPCCO_2$ | 0.27 | 0.60 |
| ΔPCREC does not Granger-cause $ΔPCCO_2$ | 7.65 | 0.01 |
| ΔPCEC does not Granger-cause $ΔPCCO_2$ | 5.67 | 0.02 |
| $ΔPCCO_2$ does not Granger-cause ΔPCGDPR | 195.50 | 0.00 |
| ΔPOP does not Granger-cause ΔPCGDPR | 389.88 | 0.00 |
| ΔPCREC does not Granger-cause ΔPCGDPR | 16.06 | 0.00 |
| ΔPCEC does not Granger-cause ΔPCGDPR | 16.15 | 0.00 |
| $ΔPCCO_2$ does not Granger-cause ΔPOP | 139.13 | 0.00 |
| ΔPCGDPR does not Granger-cause ΔPOP | 221.83 | 0.00 |
| ΔPCREC does not Granger-cause ΔPOP | 8.05 | 0.01 |
| ΔPCEC does not Granger-cause ΔPOP | 7.05 | 0.01 |
| $ΔPCCO_2$ does not Granger-cause ΔPCREC | 5.23 | 0.02 |
| ΔPCGDPR does not Granger-cause ΔPCREC | 18.38 | 0.00 |
| ΔPOP does not Granger-cause ΔPCREC | 83.50 | 0.00 |
| ΔPCEC does not Granger-cause ΔPCREC | 28.73 | 0.00 |
| $ΔPCCO_2$ does not Granger-cause ΔPCEC | 11.94 | 0.00 |
| ΔPCGDPR does not Granger-cause ΔPCEC | 135.84 | 0.00 |
| ΔPOP does not Granger-cause ΔPCEC | 15.59 | 0.00 |
| ΔPCREC does not Granger-cause ΔPCEC | 6.98 | 0.01 |

$PCCO_2$: per capita $CO_2$ emissions; PCGDPR: per capita real GDP; $PCGDPR^2$: the square of per capita real GDP; POP: population; REC: renewable energyconsumption; EC: energy consumption. Ln represents the logarithm. Fossil fuels include oil, coal, and gas. Renewable energy includes nuclear, hydro, wind, solar, geothermal, biomass in power and other renewable sources

Table 10 presents our empirical evidence concerning the causality relationship between $CO_2$ emissions, renewable energy, energy consumption, and economic growth in the short run. It is noted that we use the Granger causality test for heterogeneous panels for our analysis.

## Discussion

As presented in Table 9, our empirical results indicate that the effects are highly significant at a 1 per cent confidence level. The results are consistent across different estimation techniques, including the FMOLS and the DOLS. Economic growth and population are associated with carbon emissions in the ASEAN countries in the long run. These findings indicate that supporting economic growth in the region results in higher $CO_2$ emissions in the long run. Population growth in the region will also increase carbon emissions in the ASEAN region. Interestingly, our empirical results confirm that renewable energy will contribute to reducing carbon emissions in the long run. As such, encouraging renewable energy usage in the ASEAN countries appears to be a viable option for the countries in the region to achieve their dual objectives of supporting economic growth and limiting higher $CO_2$ emissions in the long term.

Results from Table 10 confirm the causality relationship between $CO_2$ emissions, renewable energy usage, energy consumption, and economic growth in the short run. Moreover, the results confirm the bidirectional Granger causality among each pair of selected variables, except for a unidirectional causality from $CO_2$ emissions to population. Interestingly, there is a bidirectional Granger causality among $CO_2$ emissions, economic growth, energy consumption and renewable energy.

The empirical results from this study are relatively different from previous studies examining the energy–growth–emissions nexus for the ASEAN region using panel data. Our studies confirm the effects of energy consumption, economic growth, and renewable energy usage on carbon emissions in the ASEAN countries in the past three decades. Previous studies only confirm the effects of energy consumption and economic growth on carbon emissions [19, 20]. The differences can be explained by the data period and the estimation techniques. Our study focuses more on the long-term effects to provide additional policy implications for the governments of the ASEAN countries. In addition, our causality analysis confirms a vicious circle between energy consumption, economic growth, and renewable energy. We find a bidirectional relationship between these important variables, highlighting the importance of renewable energy in the energy mix for the ASEAN countries to achieve their dual objectives of continuing to support economic growth and limiting $CO_2$ emission. Previous studies for the ASEAN countries indicate a bidirectional causality relationship between economic growth and energy consumption (the feedback hypothesis). However, they only confirm the unidirectional causality from economic growth to $CO_2$ emissions (the conservation hypothesis).

## Conclusions

Renewable energy has emerged as an important energy source for the ASEAN countries to consider in achieving their dual objectives of supporting economic growth and limiting $CO_2$ emission. Previous studies have widely investigated the dynamic relationship between carbon emissions, economic growth, and energy consumption. However, the focus on the important role of renewable energy in the energy–growth–emissions nexus for the ASEAN region in the past three decades has been under-examined. As such, this study is conducted to revisit this important relationship with a focus on renewable energy for the region.

The findings from this paper indicate that carbon emissions are associated with energy consumption. In contrast, carbon emissions are negatively related to renewable energy. These findings confirm that using energy from fossil fuel sources will further deteriorate the environmental quality as it will increase carbon emissions in the ASEAN region. In contrast, our findings indicate that renewable energy reduces $CO_2$ emissions, improving environmental quality. Economic growth is associated with increased energy consumption and carbon emissions in the ASEAN countries. These findings, when considered together, form a vicious circle for the ASEAN economies. Economic growth requires energy consumption. Increased energy consumption leads to an increase in energy demand from fossil fuel sources, leading to higher $CO_2$ emissions. In this circle, only renewable energy usage in the energy mix of the ASEAN countries can support continued economic growth and reduce the negative effects on environmental quality. The causality tests confirm a bidirectional Granger causality among $CO_2$ emissions, economic growth, energy consumption and renewable energy usage. These findings from the causality tests further confirm the vicious circle among them.

These findings from the bidirectional causality have provided vitally important policy implications for the governments of the ASEAN countries and other emerging markets. *First*, an interactive impact among carbon emissions, economic growth, energy consumption and renewable energy usage implies that any economic plans or strategies on economic growth will lead to the trade-offs between carbon emissions and energy consumption. Energy consumption is required to support economic growth, leading to $CO_2$ emissions. As such, renewable energy may supplement fossil fuel energy sources in the energy mix in the transitional period. It then becomes the substitute in response to higher demand for energy consumption, resulting from economic growth. This energy source contributes to economic growth in the ASEAN region. Yet, there is still an environment-related concern regarding economic growth and energy consumption. Recent targets and commitments regarding renewable energy usage among the ASEAN members are on the right track. Efforts to increase the share of renewable energy in the total primary energy supply should be encouraged. Alternative solutions towards taking technological advances in adopting and using renewable energy could be considered to reduce carbon emissions. *Second*, the governments should continue encouraging firms to produce non-energy intensive and environmentally friendly goods and adopt strict environmental regulations) to discourage firms from using less-friendly-with-the-environment technology. All in all, the governments of the ASEAN countries may need better coordination to implement policies and strategies focusing on the important role of renewable energy in combating climate change. The intergovernmental bodies such as the ASEAN Center for Energy, an intergovernmental organization within the ASEAN structure representing the 10 ASEAN Member States' interests in the energy sector, should be tasked with policy agenda regarding extending renewable energy use in the energy mix of all ASEAN countries, considering the current standing of each ASEAN country in their particular energy mix, economic growth level, budget constraints and their social characteristics. These policy briefs ensure that proposed policies can be implemented with positive spillover effects across all ten countries in the region.

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**Author contributions**
Conceptualization: HQB, TT, ATV and DHV; methodology: DHV; formal analysis and investigation: HQB, TT, ATV and DHV; writing—original draft preparation: HQB, TT, ATV and DHV; writing—review and editing: HQB, TT, ATV and DHV; funding acquisition: HQB, TT; resources: TT and DHV; supervision: HQB and DHV.

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**Availability of data and materials**
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## Declarations

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable

**Competing interests**
The authors declare that they have no competing interests.

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**References**

1. IEA (2022) Southeast Asia Energy Outlook 2022—Analysis. In: IEA. https://www.iea.org/reports/southeast-asia-energy-outlook-2022. Accessed 11 May 2023
2. Kittner N (2022) ASEAN needs to work together on green energy. In: East Asia Forum. https://www.eastasiaforum.org/2022/06/21/asean-needs-to-work-together-on-green-energy/. Accessed 11 May 2023
3. Yu K (2023) Renewable Energy Investment in ASEAN: Unfolding Trajectories and Challenges. In: FULCRUM. https://fulcrum.sg/aseanfocus/renewable-energy-investment-in-asean-unfolding-trajectories-and-challenges/. Accessed 11 May 2023
4. US EPA (2017) Part One: The Multiple Benefits of Energy Efficiency and Renewable Energy. https://www.epa.gov/statelocalenergy/part-one-multiple-benefits-energy-efficiency-and-renewable-energy. Accessed 11 May 2023

5. Şener ŞEC, Sharp JL, Anctil A (2018) Factors impacting diverging paths of renewable energy: a review. Renew Sustain Energy Rev 81:2335–2342. https://doi.org/10.1016/j.rser.2017.06.042
6. Saboori B, Sulaiman J (2013) CO2 emissions, energy consumption and economic growth in Association of Southeast Asian Nations (ASEAN) countries: a cointegration approach. Energy 55:813–822. https://doi.org/10.1016/j.energy.2013.04.038
7. Vo AT, Vo DH, Le QT-T (2019) CO2 emissions, energy consumption, and economic growth: new evidence in the ASEAN countries. J Risk Fin Man 12:145. https://doi.org/10.3390/jrfm12030145
8. Vo DH, Vo AT (2021) Renewable energy and population growth for sustainable development in the Southeast Asian countries. Energy Sustain Soc 11:30. https://doi.org/10.1186/s13705-021-00304-6
9. Anwar A, Siddique M, Dogan E, Sharif A (2021) The moderating role of renewable and non-renewable energy in environment-income nexus for ASEAN countries: evidence from Method of Moments Quantile Regression. Renew Energy 164:956–967. https://doi.org/10.1016/j.renene.2020.09.128
10. Tan Y, Uprasen U (2021) Carbon neutrality potential of the ASEAN-5 countries: implications from asymmetric effects of income inequality on renewable energy consumption. J Environ Manag. https://doi.org/10.1016/j.jenvman.2021.113635
11. Saboori B, Sulaiman J, Mohd S (2016) Environmental Kuznets curve and energy consumption in Malaysia: a cointegration approach. Energy Sour 11:861–867. https://doi.org/10.1080/15567249.2012.662264
12. Heidari H, Turan Katircioğlu S, Saeidpour L (2015) Economic growth, CO2 emissions, and energy consumption in the five ASEAN countries. Int J Elec Power Energy Syst 64:785–791. https://doi.org/10.1016/j.ijepes.2014.07.081
13. Aslan A, Destek MA, Okumus I (2018) Bootstrap rolling window estimation approach to the analysis of the Environment Kuznets Curve hypothesis: evidence from the USA. Environ Sci and Pollut Res 25:2402–2408
14. Al-Mulali U, Saboori B, Ozturk I (2015) Investigating the environmental Kuznets curve hypothesis in Vietnam. Energy Policy 76:123–131. https://doi.org/10.1016/j.enpol.2014.11.019
15. Fakih A, Marrouch W (2019) Environmental Kuznets curve, a mirage? A nonparametric analysis for MENA countries. Inter Adv in Econ Res 25:113–119
16. Zambrano-Monserrate MA, Silva-Zambrano CA, Davalos-Penafiel JL et al (2018) Testing environmental Kuznets curve hypothesis in Peru: the role of renewable electricity, petroleum and dry natural gas. Renew Sustain Energy Rev 82:4170–4178
17. Le TH, Quah E (2018) Income level and the emissions, energy, and growth nexus: evidence from Asia and the Pacific. Inter Econ 156:193–205. https://doi.org/10.1016/j.inteco.2018.03.002
18. Churchill SA, Inekwe J, Ivanovski K, Smyth R (2018) The environmental Kuznets curve in the OECD: 1870–2014. Energy Econ 75:389–399
19. Shahbaz M, Haouas I, Van Hoang TH (2019) Economic growth and environmental degradation in Vietnam: is the environmental Kuznets curve a complete picture? Emer Mar Rev 38:197–218
20. Tzeremes P (2018) Time-varying causality between energy consumption, CO 2 emissions, and economic growth: evidence from US states. Environ Sci Pollut Res 25:6044–6060
21. Kalaitzidakis P, Mamuneas T, Stengos T (2018) Greenhouse emissions and productivity growth. J Risk Finan Man 11:38
22. Ang JB (2008) Economic development, pollutant emissions and energy consumption in Malaysia. J Pol Mod 30:271–278. https://doi.org/10.1016/j.jpolmod.2007.04.010
23. Azlina AA, Mustapha NHN (2012) Energy, economic growth and pollutant emissions nexus: the case of Malaysia. Procedia Soc Behav Sci 65:1–7. https://doi.org/10.1016/j.sbspro.2012.11.082
24. Hwang J-H, Yoo S-H (2014) Energy consumption, CO2 emissions, and economic growth: evidence from Indonesia. Qual Quant 48:63–73. https://doi.org/10.1007/s11135-012-9749-5
25. Shahzad SJH, Kumar RR, Zakaria M, Hurr M (2017) Carbon emission, energy consumption, trade openness and financial development in Pakistan: a revisit. Renew Sustain Energy Rev 70:185–192
26. Zaidi SAH, Hou F, Mirza FM (2018) The role of renewable and non-renewable energy consumption in CO 2 emissions: a disaggregate analysis of Pakistan. Environ Sci and Pollut Res 25:31616–31629
27. Raza SA, Shah N (2018) Testing environmental Kuznets curve hypothesis in G7 countries: the role of renewable energy consumption and trade. Environ Sci and Pollut Res 25:26965–26977
28. Solarin SA, Al-Mulali U, Ozturk I (2017) Validating the environmental Kuznets curve hypothesis in India and China: the role of hydroelectricity consumption. Renew Sustain Energy Rev 80:1578–1587
29. Bekhet HA, Othman NS (2018) The role of renewable energy to validate dynamic interaction between CO2 emissions and GDP toward sustainable development in Malaysia. Energy Econ 72:47–61. https://doi.org/10.1016/j.eneco.2018.03.028
30. Chandran VGR, Tang CF (2013) The impacts of transport energy consumption, foreign direct investment and income on CO2 emissions in ASEAN-5 economies. Renew Sustain Energy Rev 24:445–453. https://doi.org/10.1016/j.rser.2013.03.054
31. Sulaiman C, Abdul-Rahim AS (2017) The relationship between CO 2 emission, energy consumption and economic growth in Malaysia: a three-way linkage approach. Environ Sci Pollut Res 24:25204–25220
32. Alam MS, Duraisamy P, Siddik AB et al (2023) The impacts of globalization, renewable energy, and agriculture on CO2 emissions in India: contextual evidence using a novel composite carbon emission-related atmospheric quality index. Gon Res 119:384–401. https://doi.org/10.1016/j.gr.2023.04.005
33. Mahmood H, Alkhateeb TTY, Tanveer M, Mahmoud DHI (2021) Testing the energy-environmental Kuznets curve hypothesis in the renewable and non-renewable energy consumption models in Egypt. Int J Environ Res Pub Health 18:7334. https://doi.org/10.3390/ijerph18147334
34. Lei YT, Ma CQ, Mirza N, Ren YS, Narayan SW, Chen XQ (2022) A renewable energy microgrids trading management platform based on permissioned blockchain. Ener Econ 115:106375. https://doi.org/10.1016/j.eneco.2022.106375
35. Mahmood H (2022) Consumption and territory based CO 2 emissions, renewable energy consumption, exports and imports nexus in South America: spatial analyses. Pol J Environ Stud 31:1183–1191. https://doi.org/10.15244/pjoes/141298
36. Yang Q, Huo J, Saqib N, Mahmood H (2022) Modelling the effect of renewable energy and public-private partnership in testing EKC hypothesis: evidence from methods moment of quantile regression. Renew Energy 192:485–494. https://doi.org/10.1016/j.renene.2022.03.123
37. Ren YS, Boubaker S, Liu PZ, Weber O (2023) How does carbon regulatory policy affect debt financing costs? Empirical evidence from China. Q Rev Econ Finance 90:77–90. https://doi.org/10.1016/j.qref.2023.05.006
38. Ren YS, Apergis N, Ma C, Baltas K, Jiang Y, Liu JL (2021) FDI, economic growth, and carbon emissions of the Chinese steel industry: new evidence from a 3SLS model. Envi Sci and Pollu Res 28(37):52547–52564
39. Ren YS, Ma CQ, Apergis N, Sharp B (2021) Responses of carbon emissions to corruption across Chinese provinces. Ener Econ 98:105241. https://doi.org/10.1016/j.eneco.2021.105241
40. Hassan ST, Batool B, Sadiq M, Zhu B (2022) How do green energy investment, economic policy uncertainty, and natural resources affect greenhouse gas emissions? A Markov-switching equilibrium approach. Environ Impact Assess Rev 97:106887. https://doi.org/10.1016/j.eiar.2022.106887
41. Hassan ST, Danish K-D et al (2020) Role of institutions in correcting environmental pollution: an empirical investigation. Sustain Cities Soc 53:101901. https://doi.org/10.1016/j.scs.2019.101901
42. Awan A, Sadiq M, Hassan ST et al (2022) Combined nonlinear effects of urbanization and economic growth on CO2 emissions in Malaysia. An application of QARDL and KRLS. Urban Clim 46:101342. https://doi.org/10.1016/j.uclim.2022.101342
43. Murshed M, Mahmood H, Ahmad P et al (2022) Pathways to Argentina's 2050 carbon-neutrality agenda: the roles of renewable energy transition and trade globalization. Environ Sci Pollut Res 29:29949–29966. https://doi.org/10.1007/s11356-021-17903-7
44. Ali W, Abdullah A, Azam M (2017) The dynamic relationship between structural change and CO2 emissions in Malaysia: a cointegrating approach. Environ Sci Pollut Res 24:12723–12739. https://doi.org/10.1007/s11356-017-8888-6
45. Choi I (2001) Unit root tests for panel data. J Int Money Financ 20:249–272. https://doi.org/10.1016/S0261-5606(00)00048-6
46. Westerlund J (2007) Testing for error correction in panel data*. Oxford Bull Econ Stat 69:709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x
47. Pedroni P (2004) Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econ Theory 20:597–625. https://doi.org/10.1017/S0266466604203073

48. Hansen LP (1982) Large sample properties of generalized method of moments estimators. Econometrica 50:1029–1054. https://doi.org/10.2307/1912775
49. Andrews DWK, Lu B (2001) Consistent model and moment selection procedures for GMM estimation with application to dynamic panel data models. J Econ 101:123–164. https://doi.org/10.1016/S0304-4076(00)00077-4
50. Pesaran MH, Yamagata T (2008) Testing slope homogeneity in large panels. J Econ 142:50–93. https://doi.org/10.1016/j.jeconom.2007.05.010
51. Westerlund J, Edgerton DL (2007) A panel bootstrap cointegration test. Econ Lett 97:185–190. https://doi.org/10.1016/j.econlet.2007.03.003

## Publisher's Note