CO_2 Emissions Mitigation in ASEAN Countries: The Role of Renewable Energy Use and Financial Development

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Abstract

The nations comprising the Association of Southeast Asian Nations (ASEAN) face a pressing need to enhance environmental sustainability, given their substantial reliance on fossil fuels, contributing to 5.2% of global CO_2 emissions. Thus, understanding the pivotal role of renewable energy in this context is paramount. This research employs a panel vector autoregression method to analyze the interplay of financial development, renewable energy, and CO_2 emissions across ASEAN nations from 1990 to 2020. Findings reveal that while renewable energy consumption shows an insignificant impact on carbon emissions, financial development, and economic growth significantly and positively influence emissions. Conversely, labor exhibits a notable negative correlation with CO_2 emissions. Moreover, a bidirectional relationship exists between financial development and economic growth, as well as between labor and GDP. Additionally, unidirectional links are observed from capital formation to CO_2 emissions, from renewable energy utilization to fossil fuel dependency, and from renewable energy usage to capital formation. These outcomes underscore the inadequacy of current financial systems in fostering environmental sustainability, highlighting the urgent need for integrating environmental considerations into their operations.

Keywords: renewable energy, fossil fuel, carbon emissions, panel vector autoregressive (PVAR), causality relationship, ASEAN members

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Received: 6 Mar 2024 Accepted: 2 May 2024 Published: 15 May 2024
Journal of Asian Energy Studies (2024), Vol 8, 17-37, doi:10.24112/jaes.080002

1. Introduction

High global energy prices in the early 1970s have drawn attention, research, and global energy policies toward the use of renewable energy sources, the need for sustainable development, and reserve depletion in oil-importing countries [1, 2]. On the other hand, in recent decades, economic growth in developed and emerging countries like India, China, and others has led to the significant use of fossil fuels and, consequently, high levels of greenhouse gas (GHG) emissions and other related threats [3]. Increased economic activities have concentrated carbon dioxide and other greenhouse gases, which will increase earth warming by 1 to 5 °C this century [4], while international agreements, such as Paris, emphasize that it should be below 2 °C [1]. High GHG emissions and global warming have resulted in climate change and environmental degradation [5]. Climate change has had a profound impact on various economic sectors, particularly those closely intertwined with it, such as agriculture. Understanding the association between fossil fuel use and the climate change problem is very important, and both interconnected challenges need a holistic solution [6].

Many attempts have been made to determine the link between carbon emissions and the use of renewable energy and between carbon emissions and financial development [7, 8]. Financial development provides valuable insights into potential productive investments and facilitates optimal capital allocation [9]. The growth of the financial system means making the financial market bigger, more efficient, and stronger, as well as increasing its accessibility, which can bring many benefits to the economy [9]. It should be noted that the transition to cleaner energy depends on various variables [10]. Some studies have identified a one-way connection from economic growth to renewable energy consumption or conversely [11], while others found a bidirectional relationship [12]. However, this relationship depends on how much renewable energy is consumed [13]. If renewable energies are derived from unclean and inefficient sources, they slow down economic growth by reducing productivity [14]. Evidence indicates a positive link between financial development and renewables [15].

Evidence has also demonstrated various associations between the use of renewables and environmental sustainability [16, 17]. Although using renewable energy reduces carbon emissions, public-private partnerships in the field of renewable energy are essential in reducing carbon emissions [18, 19]. While renewable energy consumption generally has a negative effect on carbon emissions in most studies, its impact on CO_2 emissions may not be significant due to high economic growth and the high use of fossil fuels [20]. A country's renewable energy policies are expected to be coherent with its development stage [21].

Several studies have discovered a significant positive correlation between financial development and environmental sustainability, while some studies have identified a less substantial impact [22]. Evidence also suggests that financial development raises carbon emissions similar to gross domestic product (GDP) [23, 24]; however, several studies also suggest that financial development can lower carbon emissions similar to the use of renewable energy [25]. Many studies, such as Eren et al. [26], highlight a positive correlation between financial development and the adoption of renewable energy. Importantly, the causal link between financial development and GDP and carbon emissions is bidirectional, further complicating the relationship [27].

ASEAN member countries include Thailand, Cambodia, Indonesia, Brunei Darussalam, Malaysia, Myanmar, Singapore, the Philippines, Vietnam, and Lao People's Democratic Republic (PDR). These countries contribute 5.2% of the total global CO_2 emissions in 2020, of which Indonesia, Thailand, Malaysia, and Vietnam are the top emitters. On average, more than 67% of these countries' total primary energy consumption comes from fossil fuels, and only 33% is obtained from renewable energy sources. Moreover, countries like Indonesia, Vietnam, Thailand,

and Malaysia significantly contribute to the overall CO_2 emissions resulting from fossil fuel combustion. These countries rank 9th, 18th, 23rd, and 24th among the top 25 CO_2-emitting countries globally, respectively [28]. In some of these countries, a large part of the total primary energy use is derived from renewable energy sources to reduce their dependency on fossil fuels and achieve environmental sustainability. For example, in Vietnam, the Philippines, Indonesia, and Malaysia, about 22.7%, 12%, 10.4%, and 8.8% of total primary energy consumption are derived from renewable energy sources.

The focus of the current study is on the sex ASEAN members, i.e., Malaysia, Philippines, Indonesia, Singapore, Thailand, and Cambodia. The rationale for choosing these nations lies in their economic significance; in terms of population, with a total population of 515 million people, they rank third globally, following India and China, which contribute to 6.5% of the total world population. Furthermore, in 2021, the total GDP of these countries has surged to 2.6 trillion US dollars (constant 2015 prices), i.e., 3.01% of the world's GDP. Notably, the three economies, i.e., Indonesia, Thailand, and the Philippines, make the greatest contributions with \$1065.6 billion, \$438.5 billion, and \$379 billion, respectively. Moreover, the total GDP for the rest of the countries, i.e., Malaysia, Singapore, and Cambodia, is 355.1, 361, and 23.7 billion dollars, respectively. The average economic growth of these countries for the last decade was 4.48%, and the highest economic growth belongs to Cambodia (5.85%), followed by the Philippines (5.02%), Indonesia (4.65%), and Singapore (4.45%). These countries have seen remarkable economic growth, leading to a significant increase in energy needs.

Fortunately, many of these countries possess immense potential for harnessing substantial amounts of renewable energy, such as hydro and biofuels. Therefore, it is essential to analyze how the use of renewable energy and the consumption of fossil fuels impact the GDP and CO_2 emissions in these countries. Moreover, these countries can amass significant financial resources, making the investigation of the impact of financial development highly intriguing. Besides the aforementioned factors, data availability was another reason for selecting them. Other ASEAN countries lack 30-year energy data, which is crucial for econometric models.

Empirical research consistently demonstrates that the majority of prior scholarly investigations about the subject of this study have used either panel data analysis or time series methodologies. A limited number of studies in the literature have examined the combined effects of financial development and the use of renewable energies on carbon emissions and economic growth separately. To the best of our knowledge, this research question has not been explored comprehensively in a multivariate panel context within the ASEAN countries' literature. This contextual approach considers how financial development and renewable resource use together affect economic growth and environmental sustainability. This makes our study a unique and valuable contribution to the existing body of knowledge in this field. In order to bridge these gaps, this study employs the panel vector autoregressive (PVAR) model to investigate the concurrent impact of renewable energy usage and financial development on economic growth and carbon emissions.

This study provides valuable insights and contributions to the existing empirical literature on energy and environmental sustainability. Initially, the study aims to fill the existing gap in empirical literature regarding the impact of financial development and the utilization of renewable resources on the GDP and carbon emissions in several ASEAN countries (Malaysia, the Philippines, Indonesia, Singapore, Thailand, and Cambodia). This study examines the energy and renewable energy consumption in ASEAN countries and compares it to other regions, providing in-depth data on CO_2 emissions in these nations. This study goes beyond the usual analysis of variables such as GDP, financial development, and CO_2 emissions. This research thoroughly explores the profound influence of key factors, such as labor and capital, on important aspects such as CO_2 emissions, GDP, and a range of diverse variables. These primary factors have been relatively overlooked in existing literature, making this study a valuable contribution to the field. This study stands out from previous research by adopting an innovative multivariate econometric technique known as the PVAR method, in contrast to traditional methods like VAR analysis and VECM models that were used in past studies.

This study is arranged as follows: The following section evaluates the empirical literature on the topic of this study. In Section 2, the method and data of the study will be presented. An overview of ASEAN energy and economic structures is discussed in Section 3. Section 4 outlines the results of the study. Section 5 concludes by suggesting some policy suggestions.

2. Literature Review

Several studies have looked at the relationship between various factors and carbon emissions. For example, Dogan and Seker [29], by employing the dynamic ordinary least square (DOLS) and the fully modified ordinary least square (FMOLS) estimators, found that an increase in the use of renewables, financial development, and trade openness can enhance environmental sustainability. In contrast, a rise in fossil fuel consumption increases CO_2 emissions. Using similar methods, Al-Mulali et al. [30] argued that the main contributors to CO_2 emissions, in the long run, are financial development, urbanization, and GDP growth. At the same time, renewable electricity, hydroelectricity, and nuclear power can reduce CO_2 emissions. Similarly, Sharif et al. [25] point out that financial development, like renewable energy use, can reduce environmental degradation. However, Yang et al. [31], using an augmented mean group method, showed that financial development increases CO_2 emissions.

A panel threshold model for OECD countries showed that a rise in the use of renewable energy directly affects the expansion of the economy. Based on the Granger causality test, the study by Bekhet et al. [32] demonstrates a one-way connection between financial development and CO_2 emissions for some Arab countries in the Persian Gulf. Using a similar methodology, Boutabba [33] found the same results between financial development, energy use, and carbon emissions. The Granger causality analysis indicates that a link between CO_2 emissions and economic growth does not exist in the Middle East and North Africa (MENA) countries; thus, policymakers can design appropriate policies to control air pollution [34]. However, Appiah [35] suggested that if such relationships exist, they should be derived from energy efficiency and technological development to reduce the negative impacts of policies on economic growth. Another causality analysis revealed a two-way link between carbon emissions, foreign direct investment (FDI), and energy use [36]. Another causality analysis for sub-Saharan African countries showed a two-way relationship between GDP and renewable energy, and economic growth causes carbon emissions [37].

The autoregressive distributed lag (ARDL) bounds test investigation results for Pakistan and Saudi Arabia show that financial development contributes to short- and long-term carbon emissions, respectively [38,39]. Another ARDL analysis showed that CO_2 emissions are determined mainly by energy use, economic growth, trade, and financial expansion [40]. Moreover, using the same methodology, Salahuddin et al. [41] found that the major determinants of CO_2 emissions are foreign direct investment, the use of electricity, and GDP in Kuwait. However, by applying the pooled mean group (PMG) estimator, other studies found that financial development and economic growth negatively affect carbon emissions [42].

Similarly, using the system-GMM model, Saidi and Mbarek [43] found that financial development, in the long run, contributes to CO_2 emissions. Other evidence using different co-integration techniques found that financial development and globalization can reduce CO_2 emissions, but energy intensity and GDP increase them [44]. Using the ARDL model, Solaymani [45] argued that in response to increases in GDP, carbon intensity, and energy intensity, CO_2 emissions increase substantially. A vector autoregression investigation result showed that GDP is one of the key drivers of CO_2 emissions in Chinese power plants in the short and long run [46]. Pejović et al. [47], using Panel VAR, showed that renewable energy can stimulate environmental quality, and the variations in GDP largely determine the majority of changes in CO_2 emissions.

Many studies have investigated the relationship between energy consumption, CO_2 emissions, and economic growth. For example, using ARDL and Granger-causality methods for ASEAN countries, Vo et al. [48] and Safitri et al. [49] found that economic growth causes CO_2 emissions and energy consumption. Using a decomposition analysis, Sandu et al. [50] showed that energy efficiency improvement and a gradual switch in the energy fuel mix have slowed down the trend of CO_2 emissions in some significant emitters in the ASEAN region. By applying a panel regression, Jermsittiparsert [51] suggested that renewable energy use increases environmental quality while fossil fuels reduce it in ASEAN countries. Islam et al. [52] found similar results by employing a pooled mean group (PMG) regression method in these countries. Liu et al. [53] also found similar results for this region using the panel unit root tests. Using the panel autoregressive distributive lag models, Gillani and Sultana [54] showed that 1% economic growth leads to a 2% increase in carbon emissions in ASEAN countries.

The literature mentioned above demonstrates the wide range of models and approaches researchers have employed; however, the panel-vector auto-regression technique has yet to be widely used. Moreover, there is a lack of research on ASEAN member nations in the literature that used this method and investigated the role of financial development, primary factors, and both renewable and nonrenewable energies on economic growth and environmental quality. Thus, despite these obstacles, this study makes an effort to investigate how financial development, the use of fossil and renewable fuels, and other factors affect carbon emissions in a subset of ASEAN nations.

3. Methodology

In this section, we first discuss the data and the variables that affect CO_2 emissions in ASEAN countries. Then, we present the study's methodology, which is an econometric method for estimating the study's model.

3.1. Data and variables

A time series of 31 years between 1990 and 2020 is used for six ASEAN countries, including Malaysia, Cambodia, Singapore, Indonesia, the Philippines, and Thailand. The study uses seven variables in its main model to estimate the effect of financial development and the use of renewables on economic growth and carbon emissions in ASEAN countries. Besides, the model includes other variables such as labor force, capital formation, GDP, fossil fuel consumption, financial development, renewable energy use, and environmental sustainability calculated by CO_2 emissions. The latter is because CO_2 emissions are the major air pollutant; a lower level of this gas provides lower abatement and more environmental sustainability. The names, symbols, units, and descriptions of the model's variables are provided in Table 1. The main source of data is the World Development Indicators (WDI) from the World Bank, supplemented by energy data from the U.S. Energy Information Administration (EIA).

Table 1: *Descriptive statistics results*

	Indicator name (unit)	Source	Mean	Max	Min	Std. dev.	Obs.
LAB	Labor force, total (million people)	WDI	32.726	136.460	1.535	36.125	186
CAP	Gross capital formation (% of GDP)	WDI	25.608	43.640	11.834	7.060	186
GDP	GDP per capita (constant 2015 US$ billion)	WDI	248.126	1049.330	1.924	309.797	186
FFE	Fossil fuel consumption (% of total final energy consumption)	EIA	70.538	99.805	17.234	25.195	186
RNE	Renewable energy consumption (% of total final energy consumption)	WDI	29.462	82.766	0.195	25.195	186
FD	Domestic credit to private sector (% of GDP)	WDI	74.076	165.72	2.174	46.349	186
CO_2	CO_2 emissions (metric tons per capita)	WDI	3.510	11.108	0.138	3.245	186

Note: variables are in natural logarithmic form.

3.2. Econometric method

Singh et al. [55] showed that financial development can stimulate economic growth by enhancing credit accessibility and promoting increased saving and investment. The transition to clean energy and energy consumption stimulates economic growth and reduces CO_2 emissions [56,57]. Solaymani and Montes [58] showed that the consumption of all kinds of energy and foreign direct investment promote economic growth, while renewable energy consumption and financial development increase environmental quality in New Zealand. Aslan et al. [59] and Magazzino [60] used the PVAR model to investigate the relationship between economic growth, energy consumption, and CO_2 emissions. They found a one-way causality from energy consumption to economic growth (GDP) (growth hypothesis).

The current study uses the PVAR method to investigate the dynamic and mutual relationships between the model's variables and the impact of financial development, renewable energy sources, and fossil fuels on GDP and carbon dioxide emissions. These kinds of models have several advantages. First, the efficiency gained from the cross-sectional dimension makes panel VARs a highly effective choice, even with a relatively short time-series dimension. Second, VAR-based impulse response functions can effectively capture delayed effects on the studied variables [61]. Third, they can effectively address the issue of individual heterogeneity [62]. Fourth, analyzing a panel of countries offers the possibility of gaining degrees of freedom [63].

This method combines panel data and vector autoregressive (VAR). Therefore, the nature of the VAR method data is the panel. Thus, six countries were evaluated between 1990 and 2020. When the number of variables involved in a cointegration regression is more than two, it becomes possible that there is more than one cointegration vector between model variables. When there are K variables in the model, there can be as many as K-1 vectors of linear independent cointegration.

Applying the Engel and Granger method, which is based on the assumption of one covariate vector, is inappropriate in a situation with more than one covariate vector. Therefore, in this study, the PVAR (panel vector autoregressive model with p lags) approach is used in the form of Johansen's method. The advantage of this method is that it can identify multiple long-term relationships, if applicable. In the analysis of PVAR models, analysis of variance and reaction functions are used, and less attention is paid to the significance criteria of coefficients and t-statistics. Therefore, the results analyzed are those related to cointegration vectors, reaction functions, and analysis of variance. Based on the explanations provided, the research models and variables based on the PVAR regression model with fixed effects can be formulated as follows:

$$X_{it} = \phi_0 + \sum_{j=1}^{p} H_j X_{it-j} + \mu_i + \epsilon_{it} \tag{1}$$

where X_{it} is the vector of endogenous variables, μ_i is the fixed effects of countries, ϵ_{it} is the vector of error terms, and H_j is the *js* polynomial matrix in which the optimal lag length of p is defined by the Schwartz information criterion (SIC). According to the natural logarithmic form of the difference of variables, the X_{it} vector can be represented as follows:

$$X_{it} = [\Delta LAB, \Delta CAP, \Delta GDP, \Delta FFE, \Delta RNE, \Delta FD, \Delta CO_2] \tag{2}$$

The matrix shape of the PVAR method, based on the variables of this study, can be formulated as equations 3-9:

$$\begin{aligned} \Delta \ln(LAB_{it}) = \phi_{1i} + \sum_{j=1}^{p} a_{1j} \Delta \ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{1j} \Delta \ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{1j} \Delta \ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{1j} \Delta \ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{1j} \Delta \ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{1j} \Delta \ln(FD_{it-j}) + \sum_{j=1}^{p} g_{1j} \Delta \ln(CO2_{it-j}) + \mu_{1i} + \epsilon_{1it} \end{aligned} \tag{3}$$

$$\begin{aligned} \Delta \ln(CAP_{it}) = \phi_{2i} + \sum_{j=1}^{p} a_{2j} \Delta \ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{2j} \Delta \ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{2j} \Delta \ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{2j} \Delta \ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{2j} \Delta \ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{2j} \Delta \ln(FD_{it-j}) + \sum_{j=1}^{p} g_{2j} \Delta \ln(CO2_{it-j}) + \mu_{2i} + \epsilon_{2it} \end{aligned} \tag{4}$$

$$\begin{aligned} \Delta \ln(GDP_{it}) = \phi_{3i} + \sum_{j=1}^{p} a_{3j} \Delta \ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{3j} \Delta \ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{3j} \Delta \ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{3j} \Delta \ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{3j} \Delta \ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{3j} \Delta \ln(FD_{it-j}) + \sum_{j=1}^{p} g_{3j} \Delta \ln(CO2_{it-j}) + \mu_{3i} + \varepsilon_{3it} \end{aligned} \tag{5}$$

$$\begin{aligned}\Delta\ln(FFE_{it}) = \phi_{4i} + \sum_{j=1}^{p} a_{4j}\Delta\ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{4j}\Delta\ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{4j}\Delta\ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{4j}\Delta\ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{4j}\Delta\ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{4j}\Delta\ln(FD_{it-j}) + \sum_{j=1}^{p} g_{4j}\Delta\ln(CO2_{it-j}) + \mu_{4i} + \varepsilon_{4it}\end{aligned} \tag{6}$$

$$\begin{aligned}\Delta\ln(RNE_{it}) = \phi_{5i} + \sum_{j=1}^{p} a_{5j}\Delta\ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{5j}\Delta\ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{5j}\Delta\ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{5j}\Delta\ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{5j}\Delta\ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{5j}\Delta\ln(FD_{it-j}) + \sum_{j=1}^{p} g_{5j}\Delta\ln(CO2_{it-j}) + \mu_{5i} + \varepsilon_{5it}\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta\ln(FD_{it}) = \phi_{6i} + \sum_{j=1}^{p} a_{6j}\Delta\ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{6j}\Delta\ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{6j}\Delta\ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{6j}\Delta\ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{6j}\Delta\ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{6j}\Delta\ln(FD_{it-j}) + \sum_{j=1}^{p} g_{6j}\Delta\ln(CO2_{it-j}) + \mu_{6i} + \varepsilon_{6it}\end{aligned} \tag{8}$$

$$\begin{aligned}\Delta\ln(CO2_{it}) = \phi_{7i} + \sum_{j=1}^{p} a_{7j}\Delta\ln(LAB_{it-j}) + \sum_{j=1}^{p} b_{7j}\Delta\ln(CAP_{it-j}) + \\ \sum_{j=1}^{p} c_{7j}\Delta\ln(GDP_{it-j}) + \sum_{j=1}^{p} d_{7j}\Delta\ln(FFE_{it-j}) + \sum_{j=1}^{p} e_{7j}\Delta\ln(RNE_{it-j}) + \\ \sum_{j=1}^{p} f_{7j}\Delta\ln(FD_{it-j}) + \sum_{j=1}^{p} g_{7j}\Delta\ln(CO2_{it-j}) + \mu_{7i} + \varepsilon_{7it}\end{aligned} \tag{9}$$

4. Results and Discussion

To estimate the P-VAR method, the first step is checking the degree of cointegration between the model variables. According to the cointegration theory, we first need to determine the time series' reliability and degree of correlation. Table 2 provides the outcomes of the Pesaran [64] cross-sectional dependence test for all variables in the study. This test determines whether there is a cross-sectional dependence in the panel model variables. It uses time series correlation coefficients for each cross-country in the panel. In this test, the null hypothesis checks the independence between cross-sections, while the opposite hypothesis examines the dependence between cross-sections. The outcomes reported in Table 2 confirm that some variables are not stationary at level, meaning that the null hypothesis of cross-sectional independence for these variables is accepted. However, they are stationary at their first differences. We conclude that the cross-sectional dependence between the model variables existed as expected.

Table 2: *CIPS Panel unit root test*

Variable	Constant		Constant & Trend	
	Statistic	p-value	Statistic	p-value
LAB	-1.804	0.100	-1.834	0.100
D(LAB)	-3.422*	0.000	-3.400*	0.001
CAP	-1.959	0.100	-2.828	0.100
D(CAP)	-5.708*	0.000	-5.021*	0.000
GDP	-2.354**	0.051	-2.516	0.100
D(GDP)	-3.540*	0.000	-3.126*	0.000
FFE	-2.211	0.100	-1.761	0.100
D(FFE)	-3.763*	0.000	-2.938**	0.031
REN	-1.408	0.100	-3.141*	0.000
D(REN)	-3.345*	0.000	-3.511*	0.000
FD	-2.963*	0.000	-3.545*	0.000
D(FD)	-3.477*	0.000	-3.079*	0.050
CO2	-1.972	0.100	-2.754	0.100
D(CO2)	-3.468*	0.000	-3.530*	0.000

Note: (*) indicate significance levels: * = 1%, ** = 5%.

ADF lag selection is based on Schwarz information criterion.

Furthermore, the reliability of the model variables and the unit root test were performed. The unit root test in this research was conducted by Im, Pesran, and Shin [65] stationary test, which is specific to the mixed data. The outcomes of the unit root test are presented in Table 3. As can be seen, the probability level of the test statistic for all variables is less than 0.05. Therefore, the null hypothesis of the existence of a unit root is not accepted, and all variables are stable. Thus, it is possible to estimate the model without worrying about spurious regression.

Table 3: *Results for the unit root test to check cross sectional dependence*

Variable	Full data	Lags (p)			
		P=1	P=2	P=3	P=4
LAB	20.945*[0.000]	20.637*[0.000]	20.337*[0.000]	20.014*[0.000]	19.700*[0.000]
CAP	2.635*[0.008]	2.694*[0.007]	2.877*[0.004]	2.993*[0.003]	3.021*[0.003]
GDP	21.180*[0.000]	20.821*[0.000]	2.454*[0.000]	20.075*[0.000]	19.688*[0.000]
FFE	2.453*[0.014]	2.339**[0.019]	2.160**[0.031]	1.668***[0.095]	1.484[0.138]
REN	4.147*[0.000]	4.305*[0.000]	4.685*[0.000]	5.061*[0.000]	5.274*[0.000]
FD	9.466*[0.000]	8.852*[0.000]	8.479*[0.000]	8.064*[0.000]	7.638*[0.000]
CO2	7.081*[0.000]	6.894*[0.000]	6.696*[0.000]	6.490*[0.000]	6.198*[0.000]

(*) denotes level of significance at 1%.

The second step is to select the optimal lag length using general criteria such as the Schwartz information criterion (SIC), the Akaike information criterion (AIC), and others. The outcomes of the AIC criterion are stated in Table 4, suggesting that the optimal lag length is 1.

Table 4: *Test for checking the optimal lag length*

Lag	LogL	LR	FPE	AIC	SC	HQ
1	1766.136	NA	2.69e-19*	-22.89514*	-21.91167*	-22.49559*
2	1807.163	74.39648	3.00E-19	-22.7888	-20.8219	-21.9897
3	1845.588	66.09064	3.49E-19	-22.6478	-19.6974	-21.4492
4	1887.661	68.43882	3.89E-19	-22.5555	-18.6216	-20.9573
5	1937.471	76.37504*	3.97E-19	-22.5663	-17.6489	-20.5685

Note: (*) denotes the selected order of lags.

In the next step, we check the presence of a long-run equilibrium connection between the model's variables using two-panel cointegration tests developed by Kao [66] and Pedroni [67]. The outcomes are provided in Table 5. The results of these tests show that cointegration among the variables exists in both the Kao test statistics and four tests of the seven test statistics of the Pedroni test. Thus, following the above-mentioned tests in the series, we conclude that a long-run equilibrium association happens between real GDP, financial development, labor force, real gross fixed capital formation, renewable energy, and fossil fuel consumption.

Table 5: *Results for two panel cointegration tests*

Statistics	Pedroni test				Kao test	
	Within-dimension					
	Statistic	Prob.	Statistic	Prob.	t-statistic	Prob.
Within-dimension						
Panel v-Statistic	-2.344	0.991	-2.788	0.997	-4.356*	0.000
Panel rho-Statistic	0.119	0.548	0.325	0.628		
Panel PP-Statistic	-4.215*	0.000	-4.039*	0.000		
Panel ADF-Statistic	-4.245*	0.000	-4.080*	0.000		
Between-dimension						
Group rho-Statistic			0.555	0.711		
Group PP-Statistic			-5.011*	0.000		
Group ADF-Statistic			-5.234*	0.000		

Note: (*) indicate the significance level of variables (*=1%).

The results of the panel VAR model are provided in Table 6. It is important to remember that, due to the theoretical nature of the VAR model, interpreting the panel VAR coefficients may not be relevant or helpful [68]. The results show that GDP and financial development contribute to CO_2 emissions, while capital formation improves environmental quality. These results support the results of previous studies such as Solaymani et al. [69], who showed that GDP stimulates carbon emissions. Moreover, GDP positively affects the labor force. This is because more or less economic growth increases and decreases the number of employees in the labor economy. Carbon emissions increase economic growth because of the consumption of fossil fuels. Previous studies, such as Jermsittiparsert [58], suggested that fossil fuels increase CO_2 emissions in ASEAN countries.

The labor force and financial development also contribute to economic growth. This is because labor is one of the major primary factors of production and, consequently, economic growth, while other factors, such as financial expansion and support, are essential. However, gross capital formation has a positive relationship with renewable energy consumption because renewable energy production is highly capital-intensive. This implies that the production of commodities such as renewable energy requires capital. Fossil fuel use also positively affects renewable energy consumption because almost all countries import oil, and changes in fossil fuel prices affect their economic growth and the use of alternative energy sources. Financial development reacts positively to CO_2 emissions because firms need more bank loans to invest in clean technologies and energies to reduce their carbon emissions. It also reacts positively to GDP, meaning that economic growth improves financial development in selected ASEAN countries.

Table 6: *Panel VAR results*

	DCO2	DLAB	DGCF	DGDP	DFFE	DREN	DFD
DCO2(-1)	0.302^b	0.022	−0.227	0.234^c	0.012	−0.131	0.365^c
	(0.000)	(0.363)	(0.189)	(0.016)	(0.544)	(0.301)	(0.015)
DLAB(-1)	0.203	0.695^b	0.030	1.898^b	−0.002	−0.253	−0.550
	(0.246)	(0.000)	(0.939)	(0.000)	(0.973)	(0.384)	(0.111)
DGCF(-1)	-0.064^d	−0.002	−0.061	−0.007	0.000	0.120^c	0.103
	(0.078)	(0.877)	(0.456)	(0.883)	(0.985)	(0.046)	(0.151)
DGDP(-1)	0.108^c	0.033^c	0.045	-0.470^b	−0.003	−0.023	0.617^b
	(0.012)	(0.017)	(0.642)	(0.000)	(0.753)	(0.751)	(0.000)
DFFE(-1)	−0.457	−0.062	−0.310	−0.498	0.057	1.008^c	−0.257
	(0.129)	(0.522)	(0.649)	(0.193)	(0.462)	(0.044)	(0.665)
DREN(-1)	−0.017	−0.007	−0.007	0.009	0.015	0.063	−0.015
	(0.657)	(0.563)	(0.935)	(0.853)	(0.116)	(0.320)	(0.841)
DFD(-1)	0.126^b	0.007	0.077	0.104^b	−0.004	−0.052	0.293^b
	(0.000)	(0.498)	(0.309)	(0.014)	(0.613)	(0.348)	(0.000)

Note: Values in parentheses are probabilities. ^{b}, ^{c}, ^{d} denote the values are significant at the level 1%, 5%, and 10%, respectively.

In panel VAR models, the insights derived from impulse response functions and causality tests offer insightful economic interpretations, thereby providing valuable recommendations for policy formulation. The results of causality relationships using the Granger test are reported in Table 7. The results show that there is a two-way causality between GDP, financial development, and CO_2 emissions, while there is a one-way causality link between capital formation and CO_2 emissions, which is from capital formation to CO_2 emissions. The results of the study by Bekhet et al. [36] demonstrate that there is a one-way connection between financial development and CO_2 emissions in Arab countries in the Persian Gulf. Other two-way relationships include labor and GDP and financial development and GDP. Acheampong et al. [41] showed that a two-way relationship exists between GDP and renewable energy, and economic growth causes carbon emissions. A one-way relationship exists from renewable energy use to capital formation and from renewable energy consumption to fossil fuel use. Aslan et al. [59] and Magazzino [60] found a one-way causality from energy consumption to economic growth (GDP) (growth hypothesis).

The first step in panel VAR implication is defining the coefficients of the variables and the causal relations between them. The second step of the application is identifying the stationary of predictions, which is performed using the roots of the companion matrix. The results of this test show that the place of all points is within the circle, suggesting that the estimates are stable (stationary) (Fig. 1).

The estimated coefficients in vector autoregression models often do not directly have an exact economic interpretation. However, the impulse response functions and the variance analysis of the prediction error obtained after estimating the vector autoregression model can contain important

Table 7: *Granger causality relationships*

	CO2	LAB	GCF	GDP	FFE	REN	FD
CO2	—	0.828	1.727	5.864^c	0.368	1.069	5.942^c
		(0.363)	(0.189)	(0.016)	(0.544)	(0.301)	(0.015)
LAB	1.347	—	0.006	72.825^b	0.001	0.759	2.548
	(0.246)		(0.939)	(0.000)	(0.973)	(0.384)	(0.110)
GCF	3.114^d	0.024	—	0.022	0.0004	3.987^c	2.067
	(0.078)	(0.877)		(0.883)	(0.985)	(0.046)	(0.151)
GDP	6.353^b	5.763^c	0.216	—	0.099	0.101	53.975^b
	(0.012)	(0.017)	(0.642)		(0.753)	(0.751)	(0.000)
FFE	2.310	0.411	0.207	1.697	—	4.076^c	0.188
	(0.129)	(0.521)	(0.649)	(0.193)		(0.044)	(0.664)
REN	0.197	0.334	0.007	0.034	2.469	—	0.040
	(0.657)	(0.563)	(0.935)	(0.853)	(0.116)		(0.841)
FD	14.313^b	0.460	1.036	6.042^b	0.256	0.880	—
	(0.000)	(0.497)	(0.309)	(0.014)	(0.613)	(0.348)	

Note: Values in parentheses are probabilities. ^{b}, ^{c}, ^{d} denote the values are significant at the level 1%, 5%, and 10%, respectively.

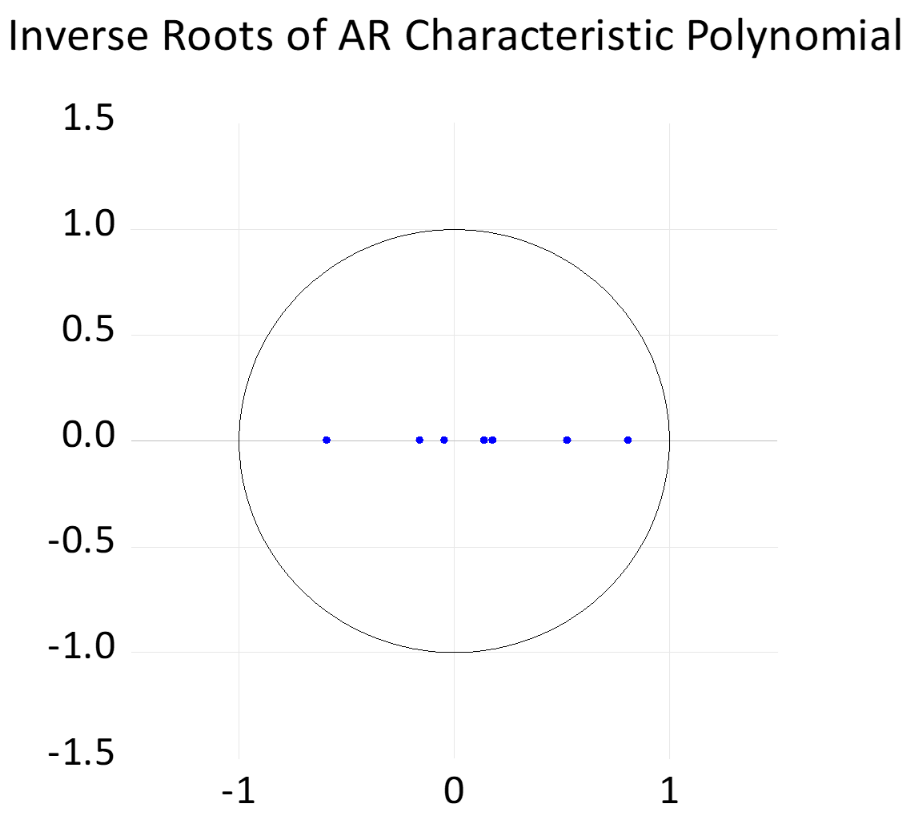

Figure 1: *Result for the stationary of predictions*

interpretations. In the PVAR model, we use impulse responses to examine the reaction of the model's variables to the changes created in each of the variables. Therefore, the effect of a certain shock on the variable is checked, and it is shown that if an unexpected change (shock) happens in a variable, how much will it affect the variable itself and other variables over different periods?

In Fig. 2 (a), we only presented the response of CO_2 emissions to the shock of all other variables in the model, and in Fig. 2 (b), the responses of other variables to CO_2 emissions are presented. In these figures, the blue lines in the middle represent the impulse response to changes in the variable under consideration, and the upper and lower margins are the positive and negative edges for the standard deviation of the instantaneous reactions at the 95% confidence level using a Monte Carlo simulation with 1000 iterations. In panel (a), we can see that CO_2 emissions react positively to GDP and financial development within the first 2 to 4 years and then tend to zero after several years. These impacts are statistically significant and are consistent with the panel VAR results. These results align with other studies, such as Charfeddine and Kahia [22]. These results also show that economic growth, which uses a high share of fossil fuels in many ASEAN countries, causes carbon emissions.

Financial development, on the other hand, has not successfully supported green energies and technologies in these countries, resulting in increased carbon emissions. Moreover, the reaction of CO_2 emissions to the shock in capital formation in the first year is zero and then negatively reacts, and after several years, tends to zero. The reaction of CO_2 emissions to the shock in fossil fuel consumption in the first year is zero, increases significantly within the next two years, and then tends to zero after several years. The response of CO_2 emissions to the shock in renewable energy consumption is negative but insignificant. Many studies showed that the response of CO_2 emissions to a shock in renewable energy consumption was negative [24,70]. The reaction of CO_2 emissions to the shock in the labor force is zero for the first year. Then CO_2 emissions positively react to its shock significantly within years three and after. However, this reaction is statistically significant and, after several years, tends to zero.

In panel (b), results show that the reactions of the labor force, economic growth, and gross fixed capital formation to the shock in CO_2 emissions are positive and tend to zero after several periods, but they are statistically significant. These three variables are strongly related to each other and affect each other. For example, both labor force and gross fixed capital formation positively affect GDP and visa verse. Therefore, they respond positively to a shock on CO_2 emissions in the same way. These results are in line with the results of the studies of Ouyang and Li [71]. Fossil fuel consumption responds negatively to the shock in CO_2 emissions, although it is not statistically significant. Furthermore, the response of financial development to the shock in CO_2 emissions is negative in the very short run. However, within the first year, it quickly increases to 0.035 and tends to be zero after several periods, which is statistically significant. These results are in line with the results of the study by Ziaei [72]. The reaction of renewable energy use to the shock in CO_2 emissions is negative (about -0.03) for the first two years, then tends to zero after several years, but it is statistically significant.

Other impulse response functions, which are not presented here, show that the response of fossil fuel consumption to renewable energy use is positive and significant, while the feedback effect is also positive and significant. The reactions of GDP to CO_2 emissions, labor, and GFCF are positive and statistically significant, and their feedback impact is also positive and significant. However, the response of GDP to financial development is not significant. The reactions of financial development to the shock in CO_2 emissions, capital formation, GDP, and renewable energy use are positive and statistically significant, and after several years, they tend to be zero. Zhang et al. [73] demonstrated a positive effect of financial development on economic growth, and Sheraz et al. [74] and Batool et al. [75] found a positive impact of financial development on CO_2 emissions.

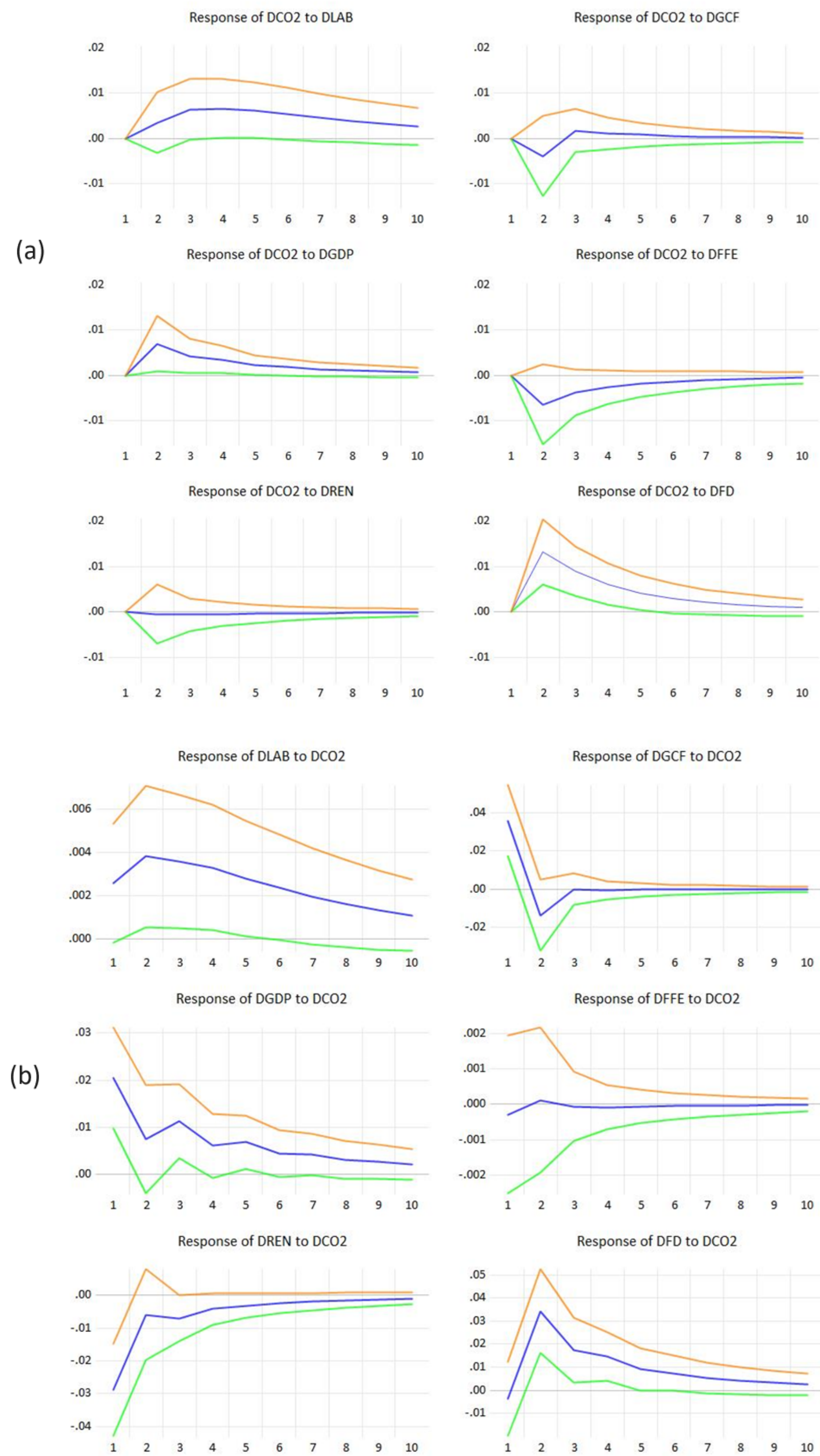

Figure 2: *Impulse response results: (a) responses of CO_2 to shock on other variables and (b) responses of other variables to a shocks on CO_2 emissions*

The interpretation of this problem is explored in the analysis of variance, and the variables account for a percentage of the prediction error's variance. Table 8 represents the variance analysis of the forecast error of CO_2 emissions in the countries studied. The results show that during the first period (short term), independent variables account for 100% of the CO_2 emissions explanation; however, as the period under consideration lengthens, the contribution of independent variables to the CO_2 emissions explanation increases. In the second period, 91.8% of the error variance in CO_2 emissions is accounted for solely by itself: 0.3% by the labor force, 0.4% by capital formation, 1.4% by GDP, 1.2% by fossil fuel consumption, 0.01% by renewable energy consumption, and 4.9% by financial development.

Hence, as the study period extends, the proportion of other explanatory variables, notably financial development, in elucidating CO_2 emissions amplifies. By the tenth period, representing the long-term outlook, the breakdown is as follows: the labor force accounts for 5%, capital formation elucidates 0.5%, GDP explains 2.2%, fossil fuel consumption justifies 1.7%, renewable energy consumption clarifies 0.03%, and financial development contributes 7.7% to CO_2 emissions. Consequently, it appears that in the short term, only financial development exerts a substantial impact on CO_2 emissions throughout the study duration. As time progresses and extends into the long term, the influence of various factors on CO_2 emissions becomes more pronounced. Beyond financial development, which initially exerts the strongest impact, other variables such as the labor force, GDP, capital formation, and the utilization of both renewable and nonrenewable energy sources exhibit increasingly significant effects on CO_2 emissions. These findings suggest a dynamic interplay among multiple factors shaping environmental outcomes, underscoring the importance of considering a comprehensive array of variables in analyzing and addressing carbon emissions over time.

Table 8: *Results of variance decomposition of panel VAR (%)*

Period	CO2	LAB	GCF	GDP	FFE	REN	FD
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	100.00	0.00	0.00	0.00	0.00	0.00	0.00
2	91.751	0.343	0.438	1.386	1.178	0.007	4.897
3	88.334	1.368	0.480	1.753	1.446	0.017	6.602
4	86.282	2.400	0.491	1.981	1.563	0.022	7.261
5	85.020	3.276	0.495	2.059	1.614	0.026	7.511
6	84.192	3.936	0.496	2.106	1.638	0.028	7.604
7	83.647	4.411	0.495	2.126	1.650	0.030	7.641
8	83.284	4.740	0.494	2.139	1.657	0.031	7.655
9	83.044	4.965	0.493	2.145	1.660	0.031	7.661
10	82.885	5.116	0.492	2.150	1.662	0.032	7.663

5. Conclusion and Policy Suggestions

Energy is the cornerstone of economic and social activities worldwide, driving the production of goods and services. Recognizing the imperative to mitigate environmental impact, many nations, including those within the ASEAN region, are pivoting towards renewable energy sources like hydro, wave, wind, and solar power. This study delved into the interplay between renewable and non-renewable energy usage, GDP, financial development, and environmental sustainability across six ASEAN countries, employing a panel vector autoregression model from 1990 to 2020.

The impulse response function results indicated that GDP positively affects environmental sustainability in ASEAN countries, which is significant. Financial development is another variable that positively impacts environmental sustainability. The outcomes also highlight that renewable energy use can improve environmental sustainability in the short term. Therefore, to achieve a high level of environmental sustainability, appropriate policies concerning the consumption and production of renewable energy are required. In this regard, providing financial incentives, creating an adequate platform and conditions for the expansion of the renewable energy industry, and creating a financial support fund for renewable energy by governments in these countries can be a way forward.

The causality relationship results also showed that GDP and financial development can affect CO_2 emissions, and CO_2 emissions can also affect both because of the role of fossil fuels in economic growth. Moreover, labor force and financial development are factors of production that improve economic growth, and the feedback effects of GDP are also significant. However, there is a one-way connection from capital formation to CO_2 emissions, from renewable energy use to capital formation, and from renewable energy use to fossil fuel consumption. According to the variance decomposition results, while CO_2 can define itself by 83% over most of the years in the ASEAN countries, the second essential variable that pollutes the air is financial development. Moreover, economic growth, labor force, and fossil fuel use affect air pollution by 2%, 5%, and 2% over the ten years.

The magnitude of the impact of renewable energy use is not high, implying that the renewable energy sector in some of these countries is in its early stages. Therefore, these economies need to enhance the renewable energy sector by providing bank loans to invest in green energy technologies. In addition, fostering economic growth can, at the same time, reduce damage to the environment.

Governments play a pivotal role in nurturing the development of renewable energies by fostering collaboration and supporting private investors, particularly given the initial investment hurdles compared to fossil fuels [76]. Phasing out fossil fuel subsidies in favor of funding renewable energy initiatives and prioritizing information and communication technologies can accelerate progress toward sustainable development goals. Global cooperation, facilitating technology transfer, stakeholder partnerships, capacity building, and robust monitoring systems are paramount in this endeavor [77]. By establishing regulatory frameworks and providing financial incentives, governments can create an enabling environment for renewable energy growth. Additionally, investing in research and development programs to advance clean technologies and promote knowledge sharing among nations can further drive the transition to a sustainable energy future.

One notable limitation of this study is the length of available time series data, with many countries lacking extensive datasets exceeding 30 years. Future research could expand by incorporating additional variables such as exchange rates and economic complexity indices to analyze their impact on economic growth and CO_2 emissions comprehensively.

Declaration of interest: None

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