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APPLIED ECONOMICS OF ENERGY AND ENVIRONMENT IN SUSTAINABILITY

The relationship between FDI, CO_2 emissions, and energy consumption in Asia-Pacific economic cooperation countries

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Abstract
This paper investigates the relationship between CO_2 emissions, energy consumption, economic growth, and foreign direct investment for a sample of Asia-Pacific Economic Cooperation Countries (APEC) countries from 1981:Q1 to 2021:Q1 employing panel data methodology. We identify cross-sectional dependence and hence utilize the cross-sectional augmented Dickey-Fuller panel unit root test for appropriate estimation. The cointegration test developed by Westerlund (2008) reveals a long-run equilibrium between CO_2 emissions, energy consumption, economic growth, and foreign direct investment. Long-run parameter estimates based on Common Correlated Effect Mean Group indicate that an increase in FDI inflows has a negative impact on air quality, supporting the pollution haven hypothesis. The cointegration test results also show that the impact of Gross Domestic Product (GDP) on CO_2 emissions varies by country in the estimation sample. In contrast to the mixed evidence on the effects of other variables, the increase in energy consumption is positively and significantly affecting CO_2 emissions in all APEC countries. Emirmahmutoglu and Kose Econ Model 28:870-876, (2011)'s panel causality test results show a bidirectional relationship between FDI and CO_2 emissions in Japan. Furthermore, there is a bidirectional causal relationship between GDP and energy consumption in Australia, China, Japan, and Singapore. Overall, empirical evidence suggests that APEC countries should adhere to strict regulations and invest in environmental-friendly clean technologies to attract foreign direct investment.

Keywords Foreign direct investment · Energy consumption · CO_2 emissions · APEC countries · Pollution haven hypothesis · Panel data analysis

Introduction

In recent years and decades, there has been a great deal of interest in the connection between economic activity and environmental degradation. In most cases, rising economic activity is followed by rising energy consumption, and rising energy demand is frequently linked to environmental quality. Although the connection between economic development, energy, and the environment has long been a focus of study, the relationship between the environment and foreign direct investments (FDI) has received less attention over the same period. Capital flow mobility has increased rapidly as a result of the globalization process. The eventual rise in demand in manufacturing and service-driven sectors around the world has resulted in nations achieving high growth rates and rising trade activities with other countries, which eventually leads to higher capital movements. However, higher growth puts a strain on developing countries in terms of energy use and environmental protection because the expansion of

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production contributes to increased energy demand, which is one of the major sources of pollutant emissions (Shahbaz et al. 2015). As a result, the existing literature mainly suggests that FDI inflows might damage the environment (Shahbaz et al. 2019). According to Moosa (2002), FDI has three important effects on the host country: economic, political, and social. The economic effects of FDI are categorized as micro and macro effects. The provision of capital, output growth, employment and wages, balance of payment, and trade flows are some of the main macroeconomic effects of FDI. On the other hand, the microeconomic effects of FDI are concerned with structural changes in economic organization and are associated with productivity level, technology transfer, local people training, and market structure. However, the context of the environment is largely neglected, and the environment is only recently recognized as an important component of FDI (Pazienza 2014).

The Asia-Pacific Economic Cooperation (APEC), which currently comprises 21 member nations, was founded in 1989 with the purpose of eliminating trade and investment obstacles and boosting economic cooperation among members. According to an APEC Report (APEC 2020), 38% of the global population inhabits in the APEC region in 2019. APEC countries also account for 61% of global nominal Gross Domestic Product (GDP) and 47% of international trade in goods and commercial services in the same year, highlighting the critical role of the region in the global economy. According to APERC (2019) survey, APEC is responsible for 57% of global energy demand, and APEC countries are recognized as the world's top five energy consumers. Increasing energy demand may indicate increased trade activity, which could lead to further environmental problems. As a result, the question of whether APEC can boost economic growth by consuming more energy without harming the environment becomes critical, making those countries an interesting case study for examining the role of FDI in the nexus of economic growth, energy, and environment.

Although FDI helps host countries' economic development, it can also lead to environmental degradation by spreading industrial activity and encouraging the use of polluting industrial goods. The literature indicates three impacts of FDI on the environment: scale, technique, and structure (composition) effects (Grossman and Krueger 1991; Copeland and Taylor 1994; Pazienza 2014; Bakhsh et al. 2017). The scale effect emphasizes the role of increased market access on the path of economic growth of host countries. On the other hand, the structure effect associates the environmental impacts with the transformation of economic structure. According to this effect, a country with a steady stream of pollution-intensive industries would eventually have significant environmental pollution (Hao et al. 2020). Finally, the technique effect is linked to the spillover effect of local firms due to technological transfers, leading to a lower emission level due to more effective use of resources. Numerous empirical studies (Suri and Chapman 1998; Antweiler et al. 2001; Cole and Elliott 2003; Hansen and Rand 2006; He 2006; Bao et al. 2011; Bakhsh et al. 2017) have been conducted on these effects, but the findings are mostly inconclusive. Hence, the role of the FDIs still deserves special attention. The relationship between FDI and the environmental standards of the host country has spawned a slew of associated hypotheses, including pollution havens and pollution halos.

The pollution haven hypothesis contends that multinational corporations relocate their environmental-polluting activities to less regulated countries if the relevant regulations in the country of origin are stringent and costly (Kisswani and Zaitouni 2021). According to the pollution haven hypothesis, increasing FDI flows has a detrimental effect on the ecosystem of host countries where the regulatory regimes are less stringent or non-existent, as supported by several empirical studies (Gray 2002; Xing and Kolstad 2002; Mihci et al. 2005; He 2006; Wagner and Timmins 2009; Tang 2015; Solarin et al. 2017). The opposing views assume that openness leads to a cleaner industry (Birdsall and Wheeler 1993), while a few other studies suppose that there is no or limited evidence for pollution havens (Jaffe et al. 1995; Cole 2004; Elliott and Shimamoto 2008). On the other hand, the pollution halo theory argues that host countries adopt tighter environmental regulations and that FDI inflows have a beneficial effect on environmental sustainability. This hypothesis contends that multinational corporations in developed countries contribute to lower carbon emissions in host countries by acquiring more environmentally friendly technologies (Mert and Caglar 2020). However, the existing empirical literature is unable to provide systematic evidence to support the existence of this hypothesis (Pazienza 2014).

Given the above background, the main objective of this article is to comprehend the relationship between economic growth, carbon dioxide (CO_2) emissions, energy consumption, and FDI for APEC countries. The study also seeks to ascertain the impact of FDIs on the environmental quality of host countries. This study contributes to the extant literature in several respects. First, the overview of the previous studies reveals that there are a limited number of studies concentrating on the energy consumption-CO_2 emissions-FDI relationship for the APEC case. Second, as opposed to previous studies utilizing data with annual frequency, we utilize a unique quarterly dataset covering the period from 1981:Q1 to 2021:Q1 enabling us to draw more reliable statistical inferences regarding the relationship between economic growth, CO_2, energy consumption, and FDI. Finally, the presence of causality among the variables under consideration has been investigated with the recently developed panel causality test by Emirmahmutoglu and Kose (2011) that can be employed for mixed panels involving stationary, non-stationary, cointegrated, and non-cointegrated series, as well as panels with cross-sectional dependence.

The organization of the paper is structured as follows. The next section contains a brief literature review on the energy consumption-CO_2 emissions-FDI relationship. The third section introduces the model, and Sect. 4 presents the methodologies utilized in the paper. Section 5 presents the results of cointegration and causality analysis on the relationship between economic growth, CO_2 emissions, energy consumption, and FDI. Finally, the last section concludes the paper and derives policy recommendations based on the empirical findings of the study.

Literature review

The relationship between environmental degradation, energy consumption, foreign direct investment, and economic growth has been investigated extensively in the literature in different countries utilizing different methodologies.

The nexus between environmental pollution and economic growth

The ongoing debates about the relationship between economic development and environmental quality remain unresolved. Higher levels of economic activity necessitate increased exploitation of natural resources, resulting in environmental degradation (Ehrlich and Holdren 1971). However, it is also assumed that there is a direct connection between economic growth and environmental quality and that higher economic growth contributes to better environmental quality (Beckerman 1992). While the relationship between economic growth and environmental quality is still debated, the Environmental Kuznets Curve (EKC), which suggests that environmental quality deteriorates until a critical stage, has resulted in a large number of empirical studies. Beyond this point, increased economic development triggers a decrease in environmental degradation, assuming an inverted-U-shaped relationship between environmental degradation and income (Grossman and Krueger 1991). Acaravci and Ozturk (2010) examined the validity of the EKC hypothesis for 19 European countries, Ren et al. (2014) for China, Boluk and Mert (2015) for Turkey, Tang and Tan (2015) for Vietnam, Shahbaz et al. (2018) for India, Waqih et al. (2019) for the South Asian region, Nasir et al. (2019) and Munir et al. (2020) for ASEAN-5 countries, Chenran et al. (2019) for Laos, Aydogan and Vardar (2020) for E7 countries. Relevant studies also show an N-shaped relationship between income and environmental degradation, implying that environmental degradation will resume once a certain level of income is reached (Grossman and Krueger 1995; Panayotou 1997; Moomaw and Unruh 1997). Bhattarai et al. (2009) for Latin American countries, Omay (2013) for Turkey, Zhang and Zhao (2014) and Liu et al. (2016) for China, Balsalobre-Lorente and Álvarez-Herranz (2016) for 17 OECD countries, Ozokcu and Ozdemir (2017) for 26 high-income OECD countries, and Allard et al. (2018) for 74 countries all support an N-shaped relationship. Many studies, however, find no support for an inverted-U or N-shaped EKC hypotheses, such as those conducted by Chandran and Tang (2013) for the ASEAN-5 economies, Al-Mulali et al. (2015) for Vietnam, Dogan and Turkekul (2016) for the USA, Mert and Bölük (2016) for the 21 Kyoto countries, and Mikayilov et al. (2018) for Azerbaijan. Shahbaz et al. (2019) and Sun et al. (2021) find an inverted-U and an N-shaped relationship between income and environmental degradation in MENA countries. For E-7 countries, Gyamfi et al. (2021) fails to confirm the existence of an N-shaped EKC but proves the existence of an inverted-U-shaped EKC. As can be seen, despite the fact that many studies have been conducted to investigate the relationship between environmental pollution and income, the results are still inconclusive due to differences between countries or the sample periods analyzed.

The nexus between energy consumption, environmental pollution, and economic growth

Environment, besides its potent findings with income, also has a strong connection with energy consumption. Following the Kyoto Protocol, the energy systems of the nations have played a major role in achieving their sustainable development goals, and the requirement of the integration of energy issues with environmental policies has become disputable (Hu and Kao 2007). The interrelated energy, environment, and income linkage is extensively investigated, and the need to consume more energy to support economic growth is widely agreed upon in literature (Magazzino 2017). However, rising energy consumption has negative environmental consequences, such as air pollution and land degradation (Hanif 2017). As a result, increased energy consumption is often cited as one of the primary reasons for increased environmental pollution (Omri et al. 2015; Asumadu-Sarkodie and Owusu 2016; Ssali et al. 2019). The vast majority of empirical studies on energy and the environment have discovered a causal relationship (Menyah and Wolde-Rufael 2010; Chandran and Tang 2013; Gokmenoglu and Taspinar 2016; Kocak and Sarkgunesi 2018; Bekun et al. 2019; Adebayo and Akinsola 2021). The relationship between economic growth and energy consumption is also one of the most contentious topics in economics. However, the debates on the causal relationship between these two variables are still controversial. Since the seminal work of Kraft and Kraft (1978) on economic growth and energy consumption, early-period studies have explored various forms of causality between economic growth and energy consumption (Akarca and Long 1980; Yu and Hwang 1984; Yu and Choi 1985; Erol and Yu 1987; Hwang and Gum 1991; Stern 1993)[1]. According to Huang et al. (2008), the disparity in findings stems from the employment of different econometric methods in prior studies. The causal linkages among these factors produces four distinct hypotheses: growth, conservation, feedback, and neutrality (Apergis and Payne 2010; Balli et al. 2020). The growth hypothesis is based on the assumption of unidirectional causality, implying that energy consumption positively impacts economic growth. This hypothesis has significant empirical support (Sengul and Tuncer 2006; Mehrara 2007; Tang et al. 2016; Nyasha et al. 2018). Each of the following studies, which are accompanied by a carbon emission variable for an integrated framework, has an identical conclusion: Ang (2007) for France, Alam et al. (2012) for Bangladesh, Alshehry and Belloumi (2015) for Saudi Arabia, Magazzino (2016a) for Kuwait, Oman, and Qatar, Acheampong (2018) and Gorus and Aydin (2019) for the MENA countries, Shahbaz et al. (2020) for 38 renewable-energy consuming countries, Ummalla and Goyari (2021) for BRICS countries. [2] The conservation hypothesis, as a second viewpoint, adopts the opposite stance as the former hypothesis. This approach, which is supported by many studies, assumes that economic development positively impacts energy consumption. For instance, Zhang and Cheng (2009)'s study reveals a unidirectional causal relationship from growth to energy consumption for China. Some other studies also support the relevant hypothesis for various countries, such as Zamani (2007) for Iran, Magazzino (2015) for Israel, Bartleet and Gounder (2010) for New Zealand, Rahman and Velayutham (2020) for five South Asian countries. The feedback hypothesis implies an existence of a bidirectional causal relationship between these two variables. The empirical studies including Erdal et al. (2008) for Turkey, Apergis and Payne (2009) for CIS countries, Belloumi (2009) for Tunisia, Dagher and Yacoubian (2012) for Lebanon, Zhixin and Xin (2011) and Wang et al. (2016) for China, Magazzino (2016b) for Italy, Antonakakis et al. (2017) for 106 countries, and Rahman (2021) for BRICS and ASEAN countries confirm the bidirectional causal relationship. Finally, the neutrality hypothesis indicates that economic growth and energy consumption do not have a causal relationship. This hypothesis is also confirmed by several studies, including Payne (2009) for the USA, Halicioglu (2009) for Turkey, Rahman and Mamun (2016) for Australia, Destek (2016) for Brazil and Malaysia, Bhattacharya et al. (2016) for 11 countries, Magazzino (2017) for APEC countries, and Fazal et al. (2021) for Pakistan.

The nexus between environmental pollution, carbon emission, economic growth, and foreign direct investment

According to mainstream economic theory, increasing FDI flows to any host nation damages the environment, especially in regions where environmental laws are weak and pollution-intensive sectors are widespread (Shahbaz et al. 2019). This is known as the pollution haven hypothesis, and it has generated considerable discussion in the literature. It focuses on the detrimental impacts of FDI on the environment from diverse sources. Many studies, using various methodologies, have confirmed the presence of the pollution haven hypothesis for various countries. Bukhari et al. (2014) for Pakistan and Solarin et al. (2017) for Ghana have used the ARDL model. Mert et al. (2019) for 26 EU countries and Essandoh et al. (2020) for low-income countries have employed panel ARDL models. Ren et al. (2014) for China and Shahbaz et al. (2019) for MENA countries have applied the GMM model for their analyses. Other research also has supported the pollution haven hypothesis, including Shahbaz et al. (2015), by employing Pedroni cointegration and the FMOLS model for low-, middle-, and high-income countries; Behera and Dash (2017), by using Pedroni cointegration, FMOLS and DOLS models for South and Southeast Asia and Nasir et al. (2019), by utilizing DOLS and FMOLS approaches for ASEAN-5 economies. Several studies, however (Tamazian and Rao 2010; Kirkulak et al. 2011; Tang and Tan 2015; Zhu et al. 2016; Zhang and Zhou 2016; Sung et al. 2018; Jugurnath and Emrith 2018; Salehnia et al. 2020), reject the pollution haven hypothesis and argue that FDI inflows reduce carbon emissions and benefit host country economies. These results are commonly attributed to the well-known pollution halo hypothesis, which argues that the negative effects of FDI can be reversed by international companies employing low-carbon technology or operating in less resource-intensive industries that are conducive to a clean environment (Zhu et al. 2016). According to this viewpoint, FDI inflows are the primary sources of minimizing

[1] See Huang et al. (2008) for a detailed empirical literature review on causal relationship between economic growth and energy consumption.

[2] Tiba and Omri (2017) conduct a detailed investigation into causal relationship between economic growth, energy consumption and carbon emissions.

environmental degradation by importing advanced or environmentally friendly technologies (Kirkulak et al. 2011; Tang and Tan 2015). The relationship between FDI and energy can also be seen here, and these investments help to boost R&D spending in order to attain improved energy efficiency (Tamazian et al. 2009). Based on the analysis of related hypotheses, the results may be country-specific, and a few other studies indicate that FDI has no significant influence on carbon emissions (Hoffmann et al. 2005; Kim and Adilov 2012; Shaari et al. 2014; Kizilkaya 2017). Utilizing bootstrap-corrected panel causality test, Yildirim (2014) found evidence in favor of pollution halo hypothesis for India, Iceland, Panama, and Zambia.

The findings of the studies on the causal relationship between FDI and CO_2 emissions are diverse, and these studies used a wide range of methodologies. The bulk of these studies discovered bidirectional causality between FDI and CO_2 emissions by employing Granger causality based on the VECM (Pao and Tsai 2011; Mutafoglu 2012; Al-Mulali and Tang 2013; Chandran and Tang 2013; Balibey 2015; Ozturk and Oz 2016), Hacker and Hatemi-J (2012) bootstrap test for causality (Kocak and Sarkgunesi 2018), Dumitrescu and Hurlin (2012) panel causality (Shahbaz et al. 2015), VAR model (Abdouli and Hammami 2017). Ozturk and Oz (2016) discovered a bidirectional causal relationship between economic development and FDI. Abdouli and Hammami (2018) discovered a bidirectional causal association between economic growth, FDI, and CO_2 emissions. Using the Toda-Yomamota causality test, Gokmenoglu and Taspinar (2016) discover a bidirectional causal relationship between CO_2 emissions, FDI, and energy consumption. However, none of the studies examined employed the causality test suggested by Emirmahmutoglu and Kose (2011). Several studies have also discovered a unidirectional causal association between relevant variables. Feridun and Sissoko (2011), Mutafoglu (2012), Olusanya (2013), Gokmenoglu and Taspinar (2016), and Abdouli and Omri (2021) reveal a unidirectional causality running from economic growth to FDI. Many other studies (Azlina and Mustapha 2012; Lee 2013; Abdouli and Hammami 2017) have explored a unidirectional causality running from FDI to economic growth. Finally, using the panel Granger causality test, Shaari et al. (2014) conclude that FDI has no long-run causal effect on CO_2 emissions.

Model and data

The main objective of this article is to examine the long-run relationship among CO_2 emissions, energy consumption, economic growth, and foreign direct investment in APEC

Table 1 Descriptive properties of the variables

Countries		$lnCO2_{it}$	$lnGDP_{it}$	$lnEC_{it}$	FDI_{it}
Australia	Mean	1.325	4.005	2.043	2.566
	Std. dev.	0.095	0.092	0.117	3.076
	Minimum	1.133	3.834	1.850	−21.29
	Maximum	1.427	14.706	2.235	20.22
Canada	Mean	1.513	2.755	2.400	2.373
	Std. dev.	0.058	0.428	0.075	2.405
	Minimum	1.409	1.947	2.262	−2.600
	Maximum	1.593	3.461	2.517	17.770
China	Mean	2.424	3.958	3.132	2.543
	Std. dev.	0.290	0.069	0.228	1.723
	Minimum	1.963	3.821	2.770	0.09
	Maximum	2.833	4.052	3.482	7.810
Indonesia	Mean	1.197	2.693	1.924	0.975
	Std. dev.	0.281	0.180	0.267	1.359
	Minimum	0.686	2.351	1.414	−3.911
	Maximum	1.614	2.997	2.312	4.909
Japan	Mean	1.862	3.872	2.680	0.192
	Std. dev.	0.051	0.071	0.069	0.416
	Minimum	1.745	3.691	2.528	−1.160
	Maximum	1.927	3.959	2.761	4.030
Malaysia	Mean	0.827	3.321	1.584	3.473
	Std. dev.	0.319	0.045	0.332	2.147
	Minimum	0.228	3.239	0.967	−2.190
	Maximum	1.232	3.395	2.025	8.910
Mexico	Mean	1.366	3.187	2.183	2.154
	Std. dev.	0.109	0.172	0.096	1.314
	Minimum	1.164	2.890	2.010	0.180
	Maximum	1.497	3.469	2.321	8.470
Philippines	Mean	0.614	2.718	1.293	1.308
	Std. dev.	0.199	0.110	0.215	1.129
	Minimum	0.248	2.546	0.855	−1.820
	Maximum	0.970	2.994	1.667	5.230
Singapore	Mean	0.347	3.920	1.366	14.322
	Std. dev.	0.170	0.189	0.289	9.524
	Minimum	−0.044	3.543	0.795	−11.070
	Maximum	0.588	4.187	1.723	43.340
Thailand	Mean	0.944	2.948	1.734	2.165
	Std. dev.	0.290	0.197	0.335	1.889
	Minimum	0.318	2.552	1.074	−7.993
	Maximum	1.230	3.236	2.111	8.535
USA	Mean	2.535	4.060	3.339	1.411
	Std. dev.	0.039	0.085	0.056	1.071
	Minimum	2.402	3.883	3.226	−1.630
	Maximum	2.594	4.185	3.408	6.250
Pooled sample	Mean	1.359	3.403	2.153	3.044
	Std. dev.	0.694	0.572	0.683	4.960
	Minimum	−0.044	1.947	0.795	−21.29
	Maximum	2.833	4.187	3.482	43.340

countries, namely, Australia, Canada, China, Indonesia, Japan, Malaysia, Mexico, Philippines, Singapore, Thailand, and the USA. As previously stated, in contrast to previous studies that used annual time series, this paper utilizes quarterly data from the Refinitiv Eikon Datastream database on CO_2 emissions, primary energy consumption, economic growth, and foreign direct investment from 1981:Q1 to 2021:Q1 (Refinitiv Eikon Datastream 2021). Following Pao and Tsai (2011), Gokmenoglu and Taspinar (2016), and Shahbaz et al. (2019), the model utilized in the paper is formulated using the equation below:

$$lnCO2_{it} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnEC_{it} + \beta_3 FDI_{it} + \varepsilon_{it} \quad (1)$$

where $lnGDP_{it}$ represents the natural log of gross domestic product per capita; $lnEC_{it}$ denotes the natural log of total primary energy consumption per capita defined in terms of million tonnes of oil equivalent (mtoe). $lnCO2_{it}$ represents the natural log of CO_2 emissions per capita (in short tonnes) employed as a proxy for the air pollution of the countries. FDI_{it} is defined as the ratio of net foreign direct investment inflows to GDP.

The pooled and cross-sectional descriptive statistics of the variables are presented in Table 1. The mean of CO_2 emissions is highest for the USA, followed by China and Japan. Singapore has the lowest average CO_2 emissions among the selected APEC countries. The mean value of the energy consumption variable is highest for the USA, followed by China and Japan. Singapore seems to have the lowest average energy consumption among the selected APEC countries. It is also noteworthy that the highest mean value of FDI_{it} is recorded for Singapore with 14.322%.

Methodology

Cross-sectional dependence and homogeneity tests

This paper applies appropriate panel data methodologies to examine cross-sectional dependence and variable heterogeneity in the first step of the panel time series analysis. Breusch and Pagan (1980) proposed the following LM test statistic for cross-sectional dependence:

$$CD_{LM} = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^2. \quad (2)$$

The LM test yields inconsistent results when N is large. As a solution to this problem, for $(N, T) \rightarrow \infty$, the existence of cross-sectional dependence among the variables of APEC countries is examined with cross-sectional dependence (CD) test proposed by Pesaran (2004). The CD statistic testing the null hypothesis of zero dependence across the panel unit is computed as follows:

$$CD = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\hat{\rho}_{ij}^2 - 1\right)} \quad (3)$$

where N and T denote the number of cross-sections and the estimation period, respectively. The null hypothesis indicates that there is no cross-sectional dependence. The test statistics $\hat{\rho}_{ij}^2$ is the estimated pair-wise correlation coefficient of the residuals obtained through simple regressions using OLS. Along with CD test, Pesaran and Yamagata (2008)'s method based on Swamy (1970) is applied to evaluate homogeneity of slope coefficients by computing the delta ($\tilde{\Delta}$) and the adjusted delta (Δ_{adj}) statistics. $\tilde{\Delta}$ statistic is a modified version of Swamy (1970) test (S) computed as follows:

$$\tilde{S} = \sum_{i=1}^{N}\left(\hat{\beta}_i - \hat{\beta}_{WFE}\right)'\frac{X_i' M_t X_i}{\tilde{\sigma}_i^2}\left(\hat{\beta}_i - \hat{\beta}_{WFE}\right) \quad (4)$$

Under the null hypothesis with $(N, T) \rightarrow \infty$, error terms are normally distributed, and $\tilde{\Delta}$ test is written as below:

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - k}{\sqrt{2k}}\right). \quad (5)$$

Adjusted $\tilde{\Delta}$ test is developed for the small sample is given as

$$\tilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - E\left(\tilde{Z}_{iT}\right)}{\sqrt{Var\left(\tilde{Z}_{iT}\right)}}\right) \quad (6)$$

Panel unit root test

This article utilizes cross-sectional augmented Dickey-Fuller (CADF) panel unit root tests to analyze the unit root properties of the variables under cross-sectional dependence. The regression model used to derive the CADF test is written as follows:

$$\Delta Z_{it} = \alpha_i + \rho_i Z_{i,t-1} + \beta_i \bar{Z}_{t-1} + \sum_{j=0}^{k}\gamma_{ij}\Delta\bar{Z}_{i,t-1} + \sum_{j=0}^{k}\delta_{ij}Z_{i,t-1} + \varepsilon_{it} \quad (7)$$

where α_i , $\bar{Z}_{t-1}$ $t_i(N,T)$ denote deterministic term, $\left(\frac{1}{N}\right)\sum_{i=1}^{N} Z_{i,t-1}$, and the t-statistics for estimation ρ_i in the equation used for computing the individual ADF statistics, respectively. Finally, CIPS statistic is computed by taking the average of individual CADF statistics based on the following formula:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T). \tag{8}$$

Panel cointegration test and panel long-run estimator

After determining the cross-sectional dependence and order of integration of variables, we used Westerlund (2008) cointegration technique to determine the long-run relationship between variables under the cross-sectional dependence. This test is built on the notion of rejecting the null hypothesis of no cointegration. The following data-generation procedure is assumed:

$$lnCO2_{it} = \delta_i' d_t + \alpha_i lnCO2_{it-1} + \lambda_i' X_{it-1} + \sum_{j=1}^{p_i} \alpha_{ij} \Delta lnCO2_{it-j} + \sum_{j=0}^{p_i} \gamma_{ij} \Delta X_{it-j} + \varepsilon_{it} \tag{9}$$

where d_t denotes the deterministic components, and X_{it} represents the matrix of independent variables, i.e., $lnGDP_{it}$, $lnEC_{it}$, and FDI_{it}. $\lambda_i = -\alpha_i \beta_i'$ and α_i denote the adjustment parameter measuring the speed at which the system corrects back to equilibrium after a sudden shock.

The test generates four test statistics (*Ga*, *Gt*, *Pa*, and *Pt*) to assess the long-run association between variables based on estimates of α_i . These statistics are produced using the least squares estimator. *Ga* and *Gt* test cointegration relationship for the panel, whereas *Pa* and *Pt* test cointegration relationship for individual panel members.

After determining the cointegrating relationship among variables, we utilized Common Correlated Effect Mean Group (CCE-MG) estimate of Pesaran (2007). The specification of the equation based on CCE-MG is written as follows:

$$lnCO2_{it} = \beta_i + \alpha_i X_{it} + \phi_i \bar{Y}_{it} + \varphi_i \bar{X}_{it} + \varepsilon_{it} \tag{10}$$

where the coefficient ϕ_i represents the elasticity of $lnCO2_{it}$ with respect to the cross-sectional averages of the dependent variables and φ_i is the elasticity of $lnCO2_{it}$with respect to the cross-sectional averages of the observed regressors.

Table 2 Cross-section dependence and homogeneity test

Cross-section dependence test				
	$lnCO2_{it}$	$lnGDP_{it}$	$lnEC_{it}$	FDI_{it}
CD-test	78.900	86.530	88.510	12.330
P value	0.000	0.000	0.000	0.000
Homogeneity test				
	$\tilde{\Delta}$	$\tilde{\Delta}_{adj}$		
Test statistics	8.180	8.339		
P value	0.000	0.000		

Table 3 Pesaran (2007) CADF panel unit root tests results

	$lnGDP_{it}$	$lnEC_{it}$	$lnCO2_{it}$	FDI_{it}
Level	−2.171	−2.126	−1.799	−2.200
1st diff	−3.145***	−4.170***	−3.088***	−5.502***

Note: *** denotes significance at 1% level. Δ is the first difference term

Table 4 Westerlund (2008) cointegration test results

Statistic	Value	*Z* value	*P* value	Robust *P* value
Gt	−3.265	−3.631	0.000	0.000
Ga	−18.901	−3.741	0.000	0.000
Pt	−10.338	−3.755	0.000	0.000
Pa	−18.931	−5.802	0.000	0.000

Table 5 CCE-MG parameter estimation results

	$lnGDP_{it}$	$lnEC_{it}$	FDI_{it}	*Constant*
Australia	0.717***	0.171***	0.0003	−0.577***
Canada	0.050*	0.989***	0.0009*	0.591**
China	0.473***	1.179***	0.003***	−2.282***
Indonesia	−0.171***	0.595***	−0.001	−2.351***
Japan	0.019	0.855***	0.001	−0.013
Malaysia	0.147**	0.662***	0.001**	−1.453
Mexico	−0.060	0.572***	0.001	−1.283***
Philippines	−0.181***	0.926***	−0.00005	−1.749***
Singapore	−0.054	1.085***	0.0002	3.003***
Thailand	0.259***	1.096***	−0.0008	2.136
USA	0.045	0.985***	0.001*	1.380***
CCE-MG	0.113	0.802***	0.0008*	−0.285

Note: *, **, and *** denote the statistical significance at 10%, 5%, and 1% level

Mean group (MG) and pooled mean group (PMG) estimators

In addition to the Westerlund (2008) test, the MG and PMG estimators are used to further explore the short- and long-run linkages between CO2 emissions, energy consumption, economic growth, and foreign direct investment. Pesaran and Smith (1995) devised mean group (MG) estimates, which estimate long-term parameters by averaging the long-term coefficients of each cross section. Pesaran et al. (1999) proposed a panel ARDL model that incorporates pooling and averaging. The pooled mean group (PMG) estimator allows for short-term coefficients and differs in error variances across groups as in MG estimators. The PMG estimator, in contrast to the MG estimator, imposes a homogeneity constraint on the long-run relationship between variables, allowing intercepts, short-run coefficients, and error variances to fluctuate freely across groups while keeping long-run coefficients constant. The PMG estimator can be specified using the panel ARDL(p,q) model as below:

$$lnCO2_{it} = \alpha_{it} + \sum_{j=1}^{p} \theta_{ij} \ln CO2_{it-j} + \sum_{j=1}^{q} \gamma_{ij} X_{it-j} + \varepsilon_{1it} \tag{11}$$

where X_{it} is the matrix containing the explanatory variables, $X_{it} = [lnGDP_{it}\ lnEC_{it}\ FDI_{it}]$. To explore short- and long-run dynamic relationship, panel ARDL(p,q) model in Eq. (11) is converted into the following error correction model (ECM):

$$\Delta lnCO2_{it} = \alpha_{it} + \phi_i \ln CO2_{it-1} + \delta_i X_{it} + \sum_{j=1}^{p-1} \rho_{ij} \Delta \ln CO2_{it-j} + \sum_{j=1}^{q-1} \lambda_{ij} X_{it-j} + \varepsilon_{it} \tag{12}$$

The equation above is further redefined by combining the error correction of the variables, yielding the following equation:

$$\Delta lnCO2_{it} = \alpha_{it} + \phi_i \left(\ln CO2_{it-1} - \left(-\frac{\delta_i}{\phi_i} \right) X_{it} \right) + \sum_{j=1}^{p-1} \rho_{ij} \Delta \ln CO2_{it-j} + \sum_{j=1}^{q-1} \lambda_{ij} X_{it-j} + \varepsilon_{it} \tag{13}$$

In Eq. (13), $-\frac{\delta_i}{\phi_i}$ represents the long-run linkages between the explained and explanatory variables, and, ρ_{ij} and λ_{ij} are the short-term parameters. Furthermore, ϕ_i is the error correction coefficient, which shows the speed of adjustment to the equilibrium level. The presence of cointegration is evidenced in case $\varphi_\mathbf{i}$ is negative. The Hausman (1978) test may be used to compare the MG and PMG models based on the homogeneity constraints imposed by the PMG estimator.

Panel causality test

To control heterogeneity and cross-sectional dependence in a panel model, Emirmahmutoglu and Kose (2011) developed a panel Granger causality test. This test is useful since it may be used on panels with stationary, non-stationary, cointegrated, and non-cointegrated series, as well as panels with cross-sectional dependency. It is also beneficial for countries dealing with turbulent periods (Seyoum et al. 2015). The Fisher (1932) test is used in this method to expand the probability values of Toda and Yamamoto (1995). Fisher test statistics, $\lambda = -2\sum_{i=1}^{N} \ln(p_i)$, p_i is the p value for Wald statistics of each unit, is not applicable in the case of dependence across cross-sectional units. As a result, Emirmahmutoglu and Kose (2011) used the bootstrap methodology to calculate the empirical distribution of the Fisher (1932) test statistics.

To examine the causality relationship among the variables, this approach utilizes an augmented bivariate VAR model with $k_i + dmaxi$ lags in heterogeneous mixed panels:

$$Y_{it} = \mu_i^Y + \sum_{j=1}^{k_i+dmaxi} B_{11,ij} Y_{i,t-j} + \sum_{j=1}^{k_i+dmaxi} B_{12,ij} X_{i,t-j} + e_{i,t}^Y \tag{14}$$

$$X_{it} = \mu_i^X + \sum_{j=1}^{k_i+dmaxi} B_{21,ij} Y_{i,t-j} + \sum_{j=1}^{k_i+dmaxi} B_{22,ij} X_{i,t-j} + e_{i,t}^x \tag{15}$$

where $dmax_i$ represents the maximal order of integration for each unit. In the first step of the test, the Augmented Dickey-Fuller (ADF) unit root test is used to determine the optimal order integration of variable for each country i ($dmax_i$) in order to test the causality from X to Y represented in Eq. (14).[3] Secondly, using the selected k_i and $dmax_i$, Eq. (14) is re-estimated by OLS; the residuals for each unit are obtained. These residuals are centered with a method proposed by Stine (1987), and the bootstrap sample of Y_{it} (Y_{it}^*) is generated in a recursive way using the bootstrap residuals. Finally, Eq. (11) is re-estimated without imposing any parameter restrictions by substituting Y_{it}^* for Y_{it}, and the individual Wald statistics are computed to test the null

[3] The optimum number of lags k_i is selected based on Akaike and Schwarz information criterions.

Table 6 Long-run and short-run parameter estimates based on MG and PMG estimators

Variables	PMG		MG	
Long-run estimates				
	Coefficient	*P* value	Coefficient	*P* value
$lnEC_{it}$	0.883	0.000	0.470	0.304
$lnGDP_{it}$	0.158	0.000	0.848	0.242
FDI_{it}	0.001	0.536	0.008	0.647
Short-run estimates				
$lnEC_{it}$	0.355	0.000	0.326	0.000
$lnGDP_{it}$	0.409	0.017	0.391	0.018
FDI_{it}	0.00003	0.842	0.0002	0.355
ECT_{it-1}	−0.032	0.049	−0.085	0.000
Constant	−0.032	0.044	−0.042	0.166

hypothesis of non-causality for each unit. These procedures may be performed for Eq. (15) to verify causality flowing from Y to X.

Empirical results and discussion

Before the assessment of the stationary features of the variables, the existence of cross-sectional dependence for APEC countries is explored using the CD test developed by Pesaran (2004). Table 2 shows evidence to reject the null hypothesis of cross-sectional dependence at the 1% level of significance for CO_2, GDP, EC, and FDI variables, indicating that the variables are cross-sectionally dependent. This finding implies that a shock in one of the APEC member nations may be propagated to the rest of the sample. The Pesaran and Yamagata (2008) homogeneity test is also used to evaluate the homogeneity of the slope coefficients, and the results are shown in Table 2. The test findings reveal indications of heterogeneity among APEC member nations.

After checking the presence of heterogeneity and cross-sectional dependency among APEC countries, we utilized CADF panel unit root test of Pesaran (2007) to identify the order of the integration of variables. Table 3 displays the results of the CADF panel unit root test. According to the results of the unit root test, all variables are integrated of order one, i.e., I (1).

Given that all variables have the same order of integration, we proceed to investigate the long-run relationship using the panel cointegration test proposed by Westerlund 2008 accounting for cross-sectional dependence. The cointegration test results illustrated in Table 4 indicate that the long-run relationship between GDP, CO_2, EC, and FDI for APEC countries is confirmed by all statistics at 1% level of significance.

Table 7 Hausman specification test results

Variables	MG	PMG	Difference	S.E.
$lnEC_{it}$	0.470	0.883	−0.413	0.489
$lnGDP_{it}$	0.848	0.158	0.689	0.774
FDI_{it}	0.008	0.001	0.006	0.019
$\chi^2(3) = 1.56$ *P* value = 0.669				

Following verification of the order of integration and long-run relationship between the variables, the CCE-MG methodology is used to estimate the long-run coefficients of Eq. (1). Table 5 displays the results of the Pesaran (2007) CCE-MG estimates for the model. The results, in general, indicate the significance of the majority of the estimated coefficients. For instance, a 1% increase in FDI results in a 0.0008% rise in CO_2 emissions, indicating that higher FDI inflows may cause environmental degradation in APEC nations. This evidence supports the pollution haven hypothesis. As for the polluting effects of economic activity, the sign and the significance of the parameters vary across the member countries. In Australia, Canada, China, Malaysia, and Thailand, the elasticity of GDP with respect to CO_2 emissions is positive, indicating that increased GDP per capita increases the CO_2 emissions in these countries. This evidence aligns with Destek and Okumus (2019) for China and Thailand and Niu et al. (2011) for Australia, China, and Thailand. On the other hand, the evidence of negative and significant GDP coefficients for Indonesia and the Philippines reveals that a rise in economic activity reduces environmental degradation in both countries. This finding is consistent with the results of Salman et al. (2019) for these countries as the authors stated that this conclusion could be explained by institutional qualities as well as by the length of the various data periods, variables, and econometric methods. Moreover, for all countries, including Indonesia and the Philippines, the elasticity of energy consumption to CO_2 emissions is positive, indicating that increasing energy consumption contributes to CO_2 emissions. Among countries, China is the highest contributor of energy consumption to CO_2 emissions. Additionally, the elasticity of CO_2 emissions to FDI is positive in Canada, China, Malaysia, and the USA. This evidence is consistent with the findings of Ren et al. (2014) for China, indicating that FDI increases CO_2 emissions. Additionally, the findings show that energy consumption has a positive and substantial effect on CO_2 emissions; a 1% increase in energy consumption leads to a 0.802% increase in the APEC nations' CO_2 emissions. The evidence for the long-run positive impact of energy consumption on APEC is consistent with that of Zaidi et al. (2019).

Following the application of Westerlund (2008) cointegration test, the short- and long-run relationship between CO_2 emissions, energy consumption, economic growth, and

Table 8 Bootstrap Granger causality between GDP and CO_2 emissions

Countries	$lnGDP_{it} \rightarrow lnCO2_{it}$			$lnCO2_{it} \rightarrow lnGDP_{it}$		
	Lag	Wald statistic	*P* value	Lag	Wald statistic	*P* value
Australia	5	7.636	0.177	5	5.815	0.325
Canada	7	46.059	0.000***	7	142.207	0.000***
China	7	322.383	0.000***	7	15.935	0.026**
Indonesia	7	10.08	0.184	7	8.108	0.323
Japan	4	60.802	0.000***	4	8.073	0.089
Malaysia	8	26.265	0.001***	8	33.771	0.000***
Mexico	6	17.985	0.006***	6	18.206	0.006***
Philippines	8	30.142	0.000***	8	13.236	0.104
Singapore	8	42.856	0.000***	8	4.641	0.795
Thailand	8	26.503	0.001***	8	8.806	0.359
USA	8	6.378	0.605	8	9.412	0.309

Table 9 Bootstrap Granger causality between FDI and CO_2 emissions

Countries	$FDI_{it} \rightarrow lnCO2_{it}$			$lnCO2_{it} \rightarrow FDI_{it}$		
	Lag	Wald statistic	*P* value	Lag	Wald statistic	*P* value
Australia	2	1.006	0.605	2	0.098	0.952
Canada	4	5.576	0.233	4	0.657	0.957
China	4	3.990	0.407	4	2.173	0.704
Indonesia	3	0.417	0.937	3	1.967	0.579
Japan	4	35.178	0.000***	4	16.305	0.003***
Malaysia	3	5.746	0.125	3	1.81	0.613
Mexico	4	1.270	0.006	4	14.443	0.006***
Philippines	1	0.074	0.866	1	0.277	0.599
Singapore	4	3.992	0.407	4	3.712	0.446
Thailand	2	1.888	0.389	2	2.187	0.335
USA	2	0.884	0.643	2	0.178	0.915
Panel (Fisher test statistic λ)		44.683*		30.071		

Table 10 Bootstrap Granger causality between EC and GDP

Countries	$lnEC_{it} \rightarrow lnGDP_{it}$			$lnGDP_{it} \rightarrow lnEC_{it}$		
	Lag	Wald statistic	*P*_value	Lag	Wald statistic	*P*_value
Australia	8	16.056	0.042**	8	19.469	0.013**
Canada	5	14.894	0.011**	5	7.075	0.215
China	6	17.768	0.007***	6	59.915	0.000***
Indonesia	7	6.224	0.514	7	15.276	0.033**
Japan	2	9.875	0.007***	2	9.027	0.011**
Malaysia	2	10.132	0.006***	2	1.914	0.384
Mexico	6	4.523	0.606	6	22.692	0.001*
Philippines	5	7.161	0.209	5	10.836	0.055*
Singapore	5	36.059	0.000***	5	16.001	0.007***
Thailand	7	7.211	0.407	7	14.122	0.049**
USA	2	5.265	0.072*	2	0.408	0.816

foreign direct investment is investigated using the MG and PMG estimators based on the estimation of the VECM form of the panel ARDL equation in Eq. (13). Table 6 displays the parameter estimates. The findings of the Hausman (1978) specification test for choosing between two estimators are also shown in Table 7. The null hypothesis of homogeneity restriction cannot be rejected based on the test statistics suggesting that the PMG estimator is a preferable alternative for estimating the link between CO_2 emissions, energy consumption, economic growth, and FDI. The error correction terms are statistically significant at the 1% level, indicating the existence of a cointegration relationship between the variables, as shown earlier by Westerlund (2008) cointegration test. The PMG findings indicate that, with the exception of foreign direct investment, all variables have a positive and significant impact on CO_2 emissions in both the long and short run. A 1% increase in energy consumption results in a 0.883% rise in CO_2 emissions in the long term. This conclusion is consistent with the CCE-MG estimator's findings. According to short-run estimates, a 1% increase in energy consumption and GDP increases CO_2 emissions by 0.355 and 0.409%, respectively.

The heterogeneous causality test proposed by Emirmahmutoglu and Kose (2011) is employed in the final stage of the empirical research to evaluate the direction of causation between GDP and CO_2, FDI and CO_2 emissions, and energy consumption and GDP. The results of bootstrap Granger causality between GDP and CO_2 emissions for 11 APEC nations are reported in Table 8. For Canada, China, Malaysia, and Mexico, the data reveal a bidirectional association between GDP and CO_2 emissions. Furthermore, a unidirectional relationship running from GDP to CO_2 emissions is evidenced for the Philippines, Singapore, Japan, and Thailand, indicating that a rise in GDP may increase CO_2 emissions in these countries. The findings are consistent with Rahman and Vu (2020) for Canada, Bekhet and Othman (2017) for Malaysia, and Munir et al. (2020) for the Philippines, Singapore, and Thailand. However, the results are inconsistent with the findings of Wang et al. (2011) for China and Munir et al. (2020) for Malaysia which find a unidirectional causality running from economic growth to CO_2 emissions and Lee and Yoo (2016) for Mexico which find a unidirectional causality running from CO_2 emissions to economic growth.

The findings of the bootstrap Granger test between FDI and CO_2 emissions using the bootstrap approach are presented in Table 9. Overall, the results reveal that foreign direct investment leads to an increase in CO_2 emissions in APEC countries. There are several studies concerning different countries supporting pollution haven hypothesis (Solarin et al. 2017; Nasir et al. 2019; Shahbaz et al. 2019). The findings back up the pollution haven theory by showing a bidirectional connection between FDI and CO_2 emissions but only for Japan. This finding is consistent with Pao and Tsai's (2011) research of BRIC countries. Furthermore, a unidirectional relationship from CO_2 to FDI is observed for Mexico.

Table 10 illustrates bootstrap Granger causality between energy consumption and GDP. The data reveal a bidirectional causality between energy consumption and GDP in Australia, China, Japan, and Singapore, verifying the feedback hypothesis. The findings of the study indicate a unidirectional causality from GDP to energy consumption for Indonesia, Mexico, the Philippines, and Thailand, supporting the conservation hypothesis. Additionally, a unidirectional causality is discovered from energy consumption to GDP in Canada and the USA, providing evidence for the growth hypothesis. These findings are in accordance with Wang et al. (2011) for China, Mahadevan and Asafu-Adjaye (2007) for Australia, Munir et al. (2020) for Indonesia and Thailand, Lee and Yoo (2016) for Mexico, and Ajmi et al. (2015) for Canada. However, the findings differ from those of Zhang and Cheng (2009) for China and Fatai et al. (2004) for Australia, which find a unidirectional causality running from GDP to energy consumption, as well as Munir et al. (2020) for Singapore, which find a unidirectional causality running from energy consumption to GDP. The findings differ from those of Shahbaz et al. (2013), who find bidirectional causality between energy consumption and economic growth in Indonesia.

The main findings of the causality tests suggest a number of implications. Unidirectional causality flowing from energy consumption to economic growth in Canada and the USA implies that energy conservation may reduce economic growth, indicating that economic growth may be achieved by increasing energy consumption. If unidirectional causation flows in the opposite direction, as it does in Indonesia, Mexico, the Philippines, and Thailand, then policies enacting conservative energy measures have little or no negative effects on economic development (Mahadevan and Asafu-Adjaye 2007). As a result, governments in these nations may reduce energy-related spending by identifying other priority areas that would help economic growth in the long run, such as education (Munir et al. 2020). However, if there is a bidirectional causation between energy consumption and economic growth, as shown by the results for four countries, then energy consumption plays a key role in promoting economic growth, and economic growth boosts energy consumption. The findings of the causality between FDI and CO_2 emissions support the pollution haven hypothesis for overall panel countries.

Conclusions

Using panel data methodology, this research explored the relationship between CO_2 emissions, energy consumption, economic growth, and foreign direct investment for a sample of APEC countries from 1981:Q1 to 2021:Q1. Test results provide evidence of cross-sectional dependence and heterogeneity among APEC countries. Therefore, cross-sectional augmented Dickey-Fuller (CADF) unit root test among the second-generation unit root tests is employed to test the stationarity levels of variables. Furthermore, we investigated the long-run equilibrium relationship across the variables using the Westerlund (2008) panel cointegration test. The Common Correlated Effects Mean Group (CCE-MG) approach proposed by Pesaran (2007) is utilized to determine the relationship between independent and dependent variables. Furthermore, short- and long-run coefficient estimations were obtained utilizing PMG analysis. Finally, the panel causality approach developed by Emirmahmutoglu and Kose (2011) is employed to find the direction of causality between the variables. The panel cointegration test results indicate that the variables are cointegrated, and there exists a long-run relationship between the variables in APEC countries. The CCE-MG test results reveal that energy consumption and FDI lead to an increase in environmental degradation as a whole panel. Similarly, PMG results also show that energy consumption was found to have a positive and significant effect on CO_2 emissions both in the long and short run. Due to the differences in the economic structures of APEC countries, the impacts of energy consumption, economic growth, and foreign direct investment on CO_2 emissions differ in a cross-country analysis. Moreover, Emirmahmutoglu and Kose (2011) bootstrap panel Granger causality demonstrates that the feedback hypothesis is valid among energy consumption and GDP in Australia, China, Japan, and Singapore. Additionally, there is a bidirectional causal relationship between FDI and CO_2 emissions in Japan. For Mexico, there is also evidence of unidirectional causality running from CO_2 emissions to FDI. Furthermore, a bidirectional relationship between GDP and CO_2 emissions has been confirmed for Canada, China, Malaysia, and Mexico.

The current trend of increasing CO_2 emissions poses a significant issue for APEC countries. To meet this problem, a comprehensive range of economic, foreign direct investment, and energy policies that promote economic growth while protecting the environment should be implemented. In general, our findings indicate that foreign direct investment and energy consumption contribute to CO_2 emissions in a subset of APEC nations. These findings highlight the importance of enacting environmentally friendly policies to reduce the impact of FDI and energy consumption on CO_2 emissions. As a result, APEC nations can reduce CO_2 emissions by implementing investment policies that encourage the use of ecologically friendly energy sources in order to attain a cleaner environment.

This study has several limitations in that we analyze the impact of primary energy consumption on environmental deterioration in the APEC nations' model. Future research could incorporate renewable energy sources into the analysis to investigate the impact of various energy sources on CO_2 emissions. Future study could investigate this connection further by employing the ecological footprint as an alternative environmental indicator.

Appendice

Table 11 Selected studies on the causality between economic growth, energy consumption, and CO_2 emissions

Author(s)	Period	Countries	Variables	Methodology	Results		
					GDP-CO_2	EC-GDP	EC-CO_2
Menyah and Wolde-Rufael (2010)	1965–2006	South Africa	GDP, CO_2, EC, CF, EMP	ARDL bound test, modified Granger causality	CO_2→GDP	EC→GDP	EC→CO_2
Alam et al. (2012)	1972–2006	Bangladesh	GDP, CO_2, EC, EL	ARDL bound test, ECM-based Granger causality	CO_2→GDP	EC→GDP	EC→CO_2 Short run EC↔CO_2 Long run
Chandran and Tang (2013)*	1971–2008	ASEAN-5 countries	GDP, CO_2, EC, FDI	Johansen cointegration test, Granger causality	GDP↔CO_2 (Indonesia, Thailand) GDP→CO_2 (Malaysia)	EC↔GDP (Malaysia) EC→GDP (Indonesia, Thailand)	EC↔CO_2 (Thailand, Malaysia) EC→CO_2 Indonesia
Shahbaz et al. (2013)	1975–2011	Indonesia	GDP, CO_2, EC, FD, TR	ARDL bound test, VECM Granger causality	GDP↔CO_2	EC↔GDP	EC↔CO_2
Yang and Zhao (2014)	1970–2008	India	GDP, CO_2, EC, CF, TR	Granger causality	GDP↔CO_2	EC→GDP	EC→CO_2

Table 11 (continued)

Author(s)	Period	Countries	Variables	Methodology	Results		
					GDP-CO_2	EC-GDP	EC-CO_2
Alshehry and Belloumi (2015)*	1971–2010	Saudi Arabia	GDP, CO_2, EC, EP	Johansen multivariate cointegration test, Granger causality	GDP↔CO_2	EC→GDP	EC→CO_2
Gokmenoglu and Taspinar (2016)	1974–2010	Turkey	GDP, CO_2, EC, FDI	ARDL bound test, Toda-Yamamoto causality	GDP≠CO_2	GDP→EC	EC↔CO_2
Lee and Yoo (2016)	1971–2007	Mexico	GDP, CO_2, EC	Johansen cointegration test, ECM-based Granger causality	CO_2→GDP	GDP→EC	EC↔CO_2
Magazzino (2016b)	1970–2006	Italy	GDP, CO_2, EC	Johansen cointegration test, Toda-Yamamoto causality test, Granger causality	GDP≠CO_2 (Granger causality)	EC≠GDP (Granger causality)	CO_2→EC (Granger causality)
Wang et al. (2016)	1990–2012	China	GDP, CO_2, EC	Johansen multivariate cointegration test, Granger causality	GDP≠CO_2	EC↔GDP	EC→CO_2
Antonakakis et al. (2017)	1971–2011	106 countries	GDP, CO_2, EC	PVAR, panel-Granger causality	CO_2→GDP (for high-income c.) GDP→CO_2 (except lower mid- income c.)	EC↔GDP	EC→CO_2
Acheampong (2018)	1990–2014	116 countries	GDP, CO_2, EC	System-GMM PVAR, Granger causality	GDP↔CO_2 Global level	EC→GDP Global level	CO_2→EC Global le.
Akalpler and Hove (2019)	1971–2014	India	GDP, CO_2, EC, CF, IMP, EXP	ARDL bound test, Granger causality	GDP≠CO_2	EC≠GDP	EC≠ CO_2
Gorus and Aydin (2019)*	1975–2014	MENA countries	GDP, CO_2, EC	Granger causality	GDP≠CO_2	EC→GDP	EC↔CO_2
Chontanawat (2020)	1971–2015	ASEAN countries	GDP, CO_2, EC	Johansen cointegration test, Granger causality	GDP≠CO_2	GDP→EC	EC↔CO_2

→, ↔, and ≠ represent unidirectional causality, bidirectional causality, and no causality, respectively.

GDP economic growth, *EC* energy consumption, *CO_2* carbon emissions, *CF* real gross fixed capital formation, *EMP* employment, *EL* electricity consumption, *EP* energy price, *IMP* imports, *EXP* exports, *FD* financial development, *TR* trade openness

*Long run causality results are given

Table 12 Selected studies on the causality between foreign direct investments and economic growth, energy consumption and CO_2 emission

Author(s)	Period	Countries	Variables	Methodology	Results		
					FDI-GDP	FDI-EC	FDI-CO_2
Pao and Tsai (2011)	1980–2007	BRIC countries	GDP, CO_2, EC, FDI	Panel cointegration, panel Granger causality	GDP→FDI	FDI↔EC	FDI↔CO_2
Al-Mulali and Tang (2013)*	1980–2009	GCC countries	GDP, CO_2, EC, FDI	Pedroni cointegration, FMOLS, Granger causality	FDI↔GDP	FDI↔EC	FDI↔CO_2
Chandran and Tang (2013)	1971–2008	ASEAN-5 countries	GDP, CO_2, EC, FDI	Johansen cointegration test, Granger causality	FDI→GDP (Thailand) FDI↔GDP (Malaysia, Indonesia)	EC→FDI (Indonesia)	FDI↔CO_2 (Indonesia) FDI→ CO_2 (Thailand, Malaysia)
Linh and Lin (2014)*	1980–2010	Vietnam	GDP, CO_2, EC, FDI	Johansen cointegration, Granger causality	FDI↔GDP	FDI↔EC	CO_2→FDI
Shahbaz et al. (2015)	1975–2012	High-, low-, and middle income countries	GDP, CO_2, EC, FDI	Pedroni cointegration, FMOLS, Dumitrescu-Hurlin causality	FDI↔GDP	FDI≠EC	FDI↔CO_2
Tang and Tan (2015)	1976–2009	Vietnam	GDP, CO_2, EC, FDI	Multivariate Johansen cointegration test, Granger causality	FDI↔GDP	EC→FDI	FDI↔CO_2
Gokmenoglu and Taspinar (2016)	1974–2010	Turkey	GDP, CO_2, EC, FDI	ARDL bound test, Toda-Yamamoto causality	GDP→FDI	EC→FDI	FDI↔CO_2
Ozturk and Oz (2016)	1974–2011	Turkey	GDP, CO_2, EC, FDI	Maki cointegration test, Granger causality	FDI↔GDP	FDI↔EC	FDI↔CO_2
Mert et al. (2019)	1990–2014	26 EU countries	GDP, CO_2, EC, FDI	Panel ARDL model, Granger causality	GDP→FDI	EC→FDI	CO_2→FDI
Essandoh et al. (2020)	1991–2014	52 countries	GDP, CO_2, EC, FDI, REC, TF	Kao and Pedroni cointegration, PMG-ARDL model, Dumitrescu-Hurlin causality	FDI→GDP high-income countries FDI≠GDP low-income countries	FDI→EC high-income countries FDI≠EC low-income countries	FDI≠ CO_2 high-income countries FDI→ CO_2 low-income countries

→, ↔, and ≠ represent unidirectional causality, bidirectional causality, and no causality, respectively

GDP economic growth, *EC* energy consumption, *CO_2* carbon emissions, *TF* trade flows, *REC* renewable energy consumption, *POP* population, *IND* industrial structure, *URB* urbanization

*Long run causality results are given

Author contribution EB: data curation, estimation of unit root tests, interpretation of empirical results, editing of the manuscript; CS: review of literature, data curation, editing of the manuscript; MSU: review of literature, drafting the article, editing of the manuscript; ANC: data curation, estimation of the model, interpretation of empirical results, editing of the manuscript.

Availability of data and materials None

Declarations

Ethics approval This article does not contain any studies with human participants performed by any of the authors.

Consent to participate No human or animal subjects were used in the study, and no questionnaire was conducted.

Consent for publication This study does not cover individual's personal data.

Competing interests The authors declare no competing interests.

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