Vo *et al. Energy, Sustainability and Society* (2022) 12:47
https://doi.org/10.1186/s13705-022-00375-z

Energy, Sustainability and Society

RESEARCH

Open Access

Revisiting the energy-growth-environment nexus in the OECD countries: An application of the CS-ARDL approach

Duc Hong Vo[1,2], Chi Minh Ho[1,2], Quan Thai Thuong Le[1,2] and Anh The Vo[1,2*]

Abstract

Background: This study revisits the energy-growth-environment nexus in the member countries of the Organization for Economic Cooperation and Development (OECD) by examining the role of trade openness, financial development, and urbanization. The cross-sectional augmented distributed lag (CS-ARDL) approach is employed to address the presence of slope homoskedasticity and cross-sectional dependence in the data set.

Results: Our empirical findings fail to confirm the validity of the environmental Kuznets curve (EKC) hypothesis for emissions of carbon dioxide (CO_2) during the period researched. CO_2 emissions have bidirectional causality with income, the share of renewable energy, and the share of nonrenewable energy. Trade openness, financial development, and urbanization play different roles in the energy-growth-environment nexus. Whereas trade openness increases CO_2 emissions, financial development reduces consumption of renewable energy. Urbanization plays a limited role in this nexus.

Conclusions: These findings lead to some policy implications. The close relationship between economic growth, CO_2 emissions, and energy consumption is highlighted, which suggests that a policy targeting one component needs to consider the impacts on the other components.

Keywords: Carbon dioxide, CS-ARDL, Economic growth, EKC, OECD, Renewable energy

Background

The energy-growth-environment nexus has long been a key concern of academics, environmentalists, and policy makers, especially in the member countries of the Organization for Economic Cooperation and Development (OECD) [1, 2]. OECD members face a dilemma among energy consumption, economic growth, and environmental degradation. Together, these countries consume a substantial proportion of total global energy, about 38% [3]. Nonetheless, the sources of energy are mainly nonrenewable (e.g., oil, natural gas, and coal), making it a principal contributor to increasingly high emissions of carbon dioxide (CO_2). The association between CO_2 emissions and global warming has attracted the attention of the governments of OECD countries over the past few decades, and they are making great efforts to reduce CO_2 emissions, one of the main causes of global warming, by adopting targets proposed by the Kyoto protocol and the Paris climate agreement [4].

The need to adopt renewable energy is widely accepted in the countries as a potential way to mitigate the environmental impacts of their economic growth targets while maintaining the level of energy consumption [5, 6]. Renewable energy is cleaner for the environment and produces fewer CO_2 emissions than energy based on fossil fuels. According to the International Energy Agency's key world energy statistics for 2020, over the past two

*Correspondence: anh.vt@ou.edu.vn

[1] Research Centre in Business, Economics & Resources, Ho Chi Minh City Open University, 97 Vo Van Tan Street, District 3, Ho Chi Minh City, Vietnam
Full list of author information is available at the end of the article

decades, electricity from renewable sources (i.e., wind and solar/photovoltaics) by OECD members increased significantly. In 2018, nearly, 750 terawatt-hours (TWh) of wind-based electricity was produced in this region, a sevenfold increase over the initial level in 2005, and the production of electricity from solar photovoltaic sources rose 300 terawatt-hours over the same period, compared with almost zero in 2005 [3]. These levels represent more than 50% of the global electricity production using wind and solar/photovoltaics. Thus, increased use of renewable energy is expected to help solve the energy-growth-environment dilemma in OECD countries.

We examine the role of trade openness, financial development, and urbanization on the energy-growth-environment nexus in the OECD countries. The theory on the role of these variables is presented below. We divide the aggregate shares of energy consumption into two categories: renewable energy and nonrenewable energy. They might have different effects on economic growth and CO_2 emissions, as documented in the empirical evidence. The consumption of nonrenewable energy increases CO_2 emissions, whereas that of renewables mitigates them. Our variable choices are similar to those in early works that emphasize the impact of real output, the share of renewable and nonrenewable energy consumption, trade openness, and financial development on CO_2 emissions in the long run. Prior works focus on a specific country, such as Turkey [7] or the United States [8], or 23 selected European countries [9]. In this study, we target the members of the OECD, because they play a leading role in controlling the level of CO_2 emissions and in boosting the ratio of renewable energy to the total energy supply. Unlike earlier studies, our research uses a different dataset and estimation techniques, which ensures the reliability of the empirical results with several robustness tests.

The impacts of trade openness, financial development, and urbanization on the nexus have been investigated in the OECD countries [10–22]. However, previous studies used first-generation estimation techniques that fail to address the common issue of cross-sectional dependence in panel country data. Using a Monte Carlo simulation experiment, Ditzen [23] concludes that when cross-sectional dependence is not addressed, empirical results are significantly biased. In addition, violation of the heterogeneity assumption in panel data analysis has a minimal effect on the results. These data issues, including those of cross-sectional dependence and slope heterogeneity, are present in the data set on OECD countries. Therefore, we employ second-generation panel data techniques, which enable us to take these two issues into account. Our model specification is largely similar to that of Dogan and Seker [24], who consider the long-run effect in the countries with significant use of renewable energy and focus on the validity of the environmental Kuznets curve (EKC) hypothesis on CO_2 emissions. We argue that focusing on the long-run effect while ignoring the short-run effect can lead to incomplete and misleading overall conclusions. Therefore, our study highlights the effects of trade openness, financial development, and urbanization on the energy-growth-environment nexus in OECD countries in both the long and short runs. We also conduct a causality analysis using a cross-sectional augmented distributed lag (CS-ARDL) approach for a long-run estimation with a large set of dynamic heterogeneous panel data that have cross-sectional dependence. The CS-ARDL approach used in this study is considered a significant innovation over the approaches used in previous empirical analyses of OECD countries on this important research topic.

Literature review

Empirical studies on the energy consumption-economic growth-environmental degradation nexus have been substantiated by numerous academic studies in the past few years. We ignore the literature on the conventional relationship, which has been widely examined and discussed in previous studies [6, 25, 26]. Instead, we focus on discussions about the role of trade openness, financial development, and urbanization in this nexus.

The role of trade in the energy-growth-environment nexus

Many papers, both theoretical and empirical, explore the interaction between trade openness and the energy-growth-environment nexus. First, the gravity model theoretically develops the link between trade openness and economic growth [27], and this link is empirically tested in a recent study [28]. Second, trade openness is related to environmental degradation through scale, composition, and technique effects [29]. The scale effect states that trade expansion increases output production and trade volume, thereby increasing the amount of pollutants and harming the environment. At the same time, the composition effect hypothesizes that trade openness can shift a country's composition of exports and imports toward the production of manufacturing-based goods, which has a negative impact on the environment. The technology effect shows that trade openness drives a transformation toward the adoption of optimally efficient technologies, thereby improving environmental quality. Trade openness contributes to a reduction in environmental degradation and plays an essential role in testing the validity of the EKC hypothesis on CO_2 emissions in OECD countries [13, 17]. The trade-environment nexus is generally used to test either the pollution haven hypothesis or the factor endowment hypothesis [30]. The pollution haven hypothesis claims that polluting industries will shift from countries or areas with strict environmental regulations to those with less concern about environmental protection. Meanwhile, the factor endowment hypothesis shows that the effect of trade openness on the environment relies on a country's production capability. A country with significant resources for producing goods that involve more pollution will have higher pollution; in contrast, a country with relatively abundant resources for the production of cleaner goods will be environmentally cleaner. The hypothesis is confirmed for China [31] by investigating the location choices of pollution-intensive enterprises using firm-level data. The empirical results show a strong connection between environmental policies and firms' choices. Firms located in eastern and western China rely on local pollution regulations, whereas others locate in provinces with different environmental legislations regarding air or water pollution.

Third, trade openness is involved in energy consumption through the aforementioned scale, composition, and technique effects, because they are closely associated with economic growth [17, 32–36]. The scale effect demonstrates that an increase in trade openness corresponds to more economic activities and production, leading to higher energy demand. The composition effect illustrates that the structure of the economy is affected by trade openness. The level of energy consumption increases if trading activities come from manufacturing-based goods, such as machinery and equipment, which require energy for operations. However, the degree of energy demand decreases if trade flows enable the transportation network to function well, making energy use more efficient. The technology effect leads to lower energy use, as trade promotes technology transfer, increasing technological improvement and energy efficiency.

Scholars have tried to develop the link between trade openness and renewable energy. Increased trade openness leads to higher levels of renewable energy, for example, in China [37, 38]. In addition, it is evident that in China, nonrenewable energy consumption has a larger impact on trade openness than renewable energy [39]. The effect of trade openness on renewable energy consumption in OECD countries has also been documented in recent studies. Zhang et al. [22] show the nonlinear link between trade openness and renewable energy consumption using a panel smooth transition model. Their study illustrates when the share of imports, a measure of trade openness, reaches a certain threshold, its effect on renewable energy consumption shifts from driving to limiting. The effect of trade openness on renewable energy consumption is most significant in Mexico and least significant in the United States.

The role of financial development in the energy-growth-environment nexus

A theory that links financial development to economic growth and vice versa has been developed in the literature [40, 41]. Levin and Levine [40] explain that because of market friction in information and transaction costs, financial markets and intermediaries emerge and play a proactive role in driving economic growth through capital accumulation and technological innovation. They also summarize contemporary economic models in which economic growth alters the financial system. For instance, in models that have a fixed cost when agents participate in financial intermediaries, economic growth reduces the important role of this fixed cost and serves as a contributing factor in the improvement of the financial system. Furthermore, Fung [41] emphasizes the interactive role between financial development and economic growth by examining the convergence of these two components. Fung believes that the growth of financial development and gross domestic product (GDP) per capita in the steady state can be determined simultaneously. The empirical results reveal strong evidence of conditional convergence, and the findings in middle- and high-income countries are consistent. The theoretical and empirical studies mentioned above illustrate the causal link between financial development and economic growth. Ahmad et al. [42] support this conclusion in their empirical analysis on China at the provincial level.

The energy economics literature has incorporated the impact of financial development on energy consumption and CO_2 emissions. Theoretically, two schools of thought illustrate how financial development affects energy use and CO_2 emissions. The first school of thought asserts that financial development supports economic growth and its components, which in turn increase CO_2 emissions. First, firms in a well-developed financial system have an incentive to reduce CO_2 emissions, because they can access better capital resources and finance potential projects at a lower cost [43]. Evidence in developing countries or transitional economies proves that the development of financial markets is beneficial for the environment [43, 44]. Second, financial development can improve corporate governance, leading to higher economic growth and lower CO_2 emissions [45]. One explanation is that well-governed corporations have greater incentives for considering the environment. Third, financial development facilitates technological innovation, boosts economic growth, and reduces CO_2 emissions [46].

The second school of energy literature hypothesizes that financial development has a positive impact on energy consumption and thus harms the environment through three channels: a direct effect, a business effect, and a wealth effect [46–48]. The direct effect hypothesizes that financial development supplements affordable credit for households and consumers to purchase durable products, which consume more energy and generate higher emissions than other goods. The business effect hypothesis shows that advanced financial development supports business expansion by entrepreneurs in terms of enabling them to hire more workers, purchase more equipment and materials, and even build more plants. A corresponding result of expanding these actions increases energy consumption and CO_2 emissions. With respect to the wealth effect, the development of the financial system generally provides an additional source of financing for equity and debt, enabling business sectors to expand. A well-functioning stock market, in particular, benefits both consumers and businesses by providing greater risk diversification and economic confidence, leading to higher economic growth, energy demand, and CO_2 emissions.

Although this theory suggests a positive effect of financial development on CO_2 emissions, empirical research presents ambiguous evidence. Researchers find that a developed financial system harms the environment, and, without a strong institutional framework, higher financial liberalization worsens CO_2 emissions [43]. Other studies document that financial development mitigates CO_2 emissions, for example, in the BRICS (Brazil, Russia, India, China, and South Africa) countries [49]. More broadly, Zeeshan et al. [50] consider whether the development of the financial system matters for environmental quality, measured by a composite index of the four main greenhouse gases. In their empirical analysis, they use a sample of 20 countries that are high income and financially developed. After issues such as heterogeneity, endogeneity, and cross-sectional dependence are controlled for, banking system development supports environment quality in the countries surveyed, but the impact is insignificant for stock market development, another measure of financial development.

From the perspective of empirical analyses, financial development increases energy consumption. They demonstrate that financial development has a positive influence on energy consumption in a subsample of 15 founding members of the European Union (EU), but no significant impact is observed on either the subsample of 12 new member states or the full sample of 27 EU member countries [47]. Empirical works have shifted attention to the impact of financial development on renewable energy. Using a sample of 25 OECD member countries, Al Manum et al. [51] illustrate that growth in equity and credit markets has a positive impact on cleaner energy production, measured by biomass and non-biomass renewable energy. Qamruzzaman and Wei [52] establish a hypothesis on bidirectional causality between financial development and renewable energy consumption, and their findings are robust to low-, middle-, and high-income groups.

The role of urbanization in the energy-growth-environment nexus

Urbanization plays an important role in economic activities and vice versa. Urbanization is a structural transformation that involves not only a shift in the structure of labor from agriculture in rural areas to industry and services in urban areas but also economic and social changes [53]. As such, urbanization is considered a source of economic growth, because the economy can take advantage of larger economies of scale and a more complex market structure in urban areas than in rural areas [54]. However, urbanization does not necessarily occur in parallel with economic growth. After urbanization reaches a certain level, its rapid growth has no impact on economic growth [54] and can even harm economic development [55, 56]. Thus, increased economic growth matters for urbanization. David and Henderson [57] hypothesize that urbanization and economic development Granger-cause each other. The current literature shows that urbanization leads to higher economic growth because of the sectoral shift from agriculture to industry and services. However, urbanization reacts to economic growth through increasing democratization or increasing fiscal decentralization. In other words, urbanization corresponds to structural changes in policies and political factors driven by economic development. These two authors confirm the causality of the two variables using a panel data analysis with instrumental variables.

In the past, urbanization received less attention in the literature on energy economics, but that is no longer the case. As urbanization has increasingly accelerated in many parts of the world, its impact on energy consumption and the environment has gained attention [58]. Ahmad et al. [59] find that in China, the flow of migration from rural to urban areas helps mitigate the negative impact on CO_2 emissions, as the process promotes development of the service sector. Furthermore, empirical studies document a nonlinear link between urbanization and environmental degradation that takes an inverted U-shape. Meanwhile, Dong et al. [60] present a double-threshold impact of urbanization on CO_2 emissions. Below a certain threshold, urbanization has no significant effect on CO_2 emissions, but a negative impact is observed in between the two thresholds.

No consensus has been achieved in empirical analyses on the impact of urbanization on the growth-energy-environment nexus. In an analysis of 29 OECD member countries over the period 1980–2011, Salim and Shafiei

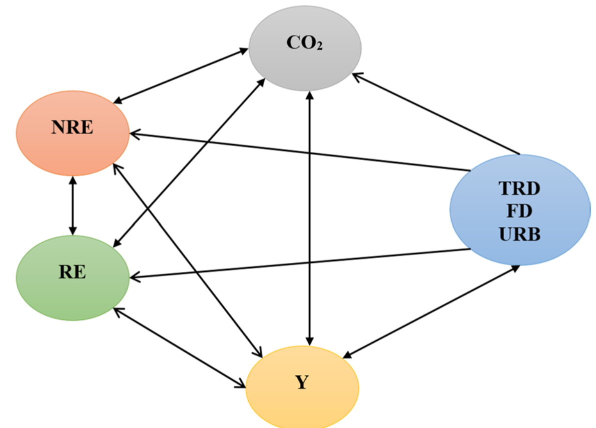

Fig. 1 Illustration of the potential causality effects. The bidirectional arrows indicate potential two-way causality between two variables, while the unidirectional arrows denote one-way causality from one variable to another. For the variable labels, see Table 1

[61] indicate that in the long run, urbanization has a significant and positive impact on the use of nonrenewable energy but not renewable energy. Using a global sample of 186 countries, Wang et al. [62] confirm the bidirectional causal relationship between economic growth and urbanization in the high- and lower-middle-income groups but not upper-middle-income groups. In addition, they confirm the importance of urbanization in increased energy consumption, though the effect differs among income groups. Wang et al. [63] reveal mixed causality patterns among urbanization, economic growth, energy consumption, and CO_2 emissions across groups of countries with different income levels using a sample of 170 countries for the 1980–2011 period.

The literature mentioned above theoretically indicates the existence of a potential bidirectional causality relationship among the variables surveyed, which is illustrated in Fig. 1. Nonetheless, empirical evidence shows a lack of consensus about the role of trade openness, financial development, and urbanization in the energy-environment-growth nexus. The rationale for this lack of consensus comes in part from the panel country data with a differential timeframe but mainly from the variable selection. Few prior studies cover all the variables that are in our analysis, but our research examines the relationship using a new approach with a CS-ARDL estimation.

Methods

Model specifications and data

This section begins with the introduction of an environmental Kuznets curve (EKC) hypothesis on CO_2 emissions based on the stochastic impacts with a regression on population, affluence, and technology (STIRPAT) model [16]. The EKC hypothesis illustrates that CO_2 emissions are linked to the level of income [5, 12, 13, 15, 19]. This hypothesis holds that high-level emissions are associated with a low income level in the first stage. The effect is expected to be reversed in a later stage with higher income. Economic growth is the main determinant of CO_2 emissions. In addition, we use an energy variable for the share of renewable and nonrenewable energy. The former is expected to mitigate the negative impact of its use on CO_2 emissions, whereas the latter has the opposite effect. Furthermore, we incorporate additional variables, including trade openness, financial development, and urbanization, as their effects on the energy-growth-environment nexus are widely documented in the literature. The following model is used in our analysis:

$$\begin{aligned} \ln CO_{2i,t} = & f(\ln Y_{i,t}, \ln Y_{i,t}^2, \ln RE_{i,t}, \ln NRE_{i,t}, \\ & \ln TRD_{i,t}, \ln FD_{i,t}, \ln URB_{i,t}) \end{aligned} \tag{1}$$

where i and t represent the number of individual countries and time periods, respectively, and ln denotes the natural logarithm. CO_2 denotes per capita carbon dioxide emissions. This dependent variable is affected by the following independent variables. Y and Y^2 are, respectively, the real per capita GDP and its squared term, illustrating the impact of economic activity on emissions. RE is the share of renewable electricity output in total electricity output, excluding hydroelectric power but including geothermal, solar, tides, wind, biomass, and biofuels. Similarly, NRE is the share of nonrenewable electricity output in total electricity output. The shares of renewable and nonrenewable energy sources are highly correlated, with a correlation value of − 0.575, as indicated in Appendix Table 10. This is because, together, the share is nearly 100%, with a tiny proportion for the share made up of hydropower.[1] The measurement of the two energy variables is similar to that of existing studies [13, 20, 24]. Finally, we add the key factors to our analysis, namely, trade openness (TRD), financial development (FD), and urbanization (URB).

Table 1 gives the labels, definitions, and measurements of all the variables. The data mainly come from the World Bank's World Development Indicators. Financial development data are extracted from a new aggregate index of financial development from the International Monetary Fund database. Svirydzenka [64] states that this index incorporates three aspects (depth, access, and efficiency), reflecting not only the development of financial institutions and financial markets but also the complex

[1] We thank the Editor for pointing out the measurement with respect to the share of renewable and nonrenewable energy.

Table 1 Data description

Variable label	Variable	Definition	Source
CO_2	CO_2 emissions	Metric tons per capita	World Bank
Y	GDP per capita	Constant 2010 US$	World Bank
RE	Share of renewable energy	Share of renewable electricity output in total electricity output	World Bank
NRE	Share of nonrenewable energy	Share of electricity production from oil, gas, and coal sources in total electricity output	World Bank
TRD	Trade openness	Percentage of GDP	World Bank
URB	Urbanization	Ratio of urban population to total population	World Bank
FD	Financial development	A broad-based index of financial development	International Monetary Fund

nature of financial development. The country list and the timeframe for each country are presented in Appendix Table 9. The OECD countries have high exports and imports, a relatively well-developed financial system, and a high degree of urbanization.

The statistical summary is shown in Table 2. The sample covers an unbalanced panel of all 37 OECD member countries over the period 1990–2015; thus, it consists of a total of 922 observations. All the variables are transformed into their natural logarithmic form to obtain standardization in the variance–covariance matrix, which is in Appendix Table 10.

Econometric techniques

We use a second-generation macroeconometric approach. Unit-root tests, cointegration tests, and long-run estimations take the slope, homogeneity, and cross-sectional dependence into account, respectively.

The first focus of our study is testing the validity of the EKC hypothesis on CO_2 emissions. Equation (1) for the long-term estimation can be constructed as

$$\ln CO_{2i,t} = \alpha_i + \alpha_1 \ln Y_{i,t} + \alpha_2 \ln Y_{i,t}^2 + \alpha_3 \ln RE_{i,t} + \alpha_4 \ln NRE_{i,t} + \alpha_5 \ln TRD_{i,t} + \alpha_6 \ln FD_{i,t} + \alpha_7 \ln URB_{i,t} + \varepsilon_{i,t} \quad (2)$$

To document the long-run effect, Eq. (2) can be estimated using the common correlated effects estimation of heterogeneous dynamic panel data models [65]. The EKC hypothesis on CO_2 emissions is supported when the estimated coefficients of economic growth and its squared term are negative and positive, respectively.

The short-run effect is then estimated using the error correction model (ECM) framework in which the error correction terms are the residuals of the long-run estimations as outlined in the following equation:

$$\begin{aligned}\Delta \ln CO_{2i,t} =& \beta_i + \sum_{j=0}^{n} \beta_{1j} \Delta \ln Y_{i,t-j} + \sum_{j=0}^{n} \beta_{2j} \Delta \ln Y_{i,t-j}^2 \\ &+ \sum_{j=0}^{n} \beta_{3j} \Delta \ln RE_{i,t-j} + \sum_{j=0}^{n} \beta_{4j} \Delta \ln NRE_{i,t-j} \\ &+ \sum_{j=0}^{n} \beta_{5j} \Delta \ln TRD_{i,t-j} + \sum_{j=0}^{n} \beta_{6j} \Delta \ln FD_{i,t-j} \\ &+ \sum_{j=0}^{n} \beta_{7j} \Delta \ln URB_{i,t-j} + \varphi ECT_{i,t} + \epsilon_{i,t}\end{aligned} \quad (3)$$

where Δ denotes the first difference, and n represents the number of optimal lags. The residuals (ϵ_{it}) are assumed to be serially independent with zero mean and a finite covariance matrix. The error correction terms ($ECT_{i,t}$) are derived from the long-run estimation by differentiating the lagged dependent variable from a set of explanatory variables.

Chudik and Pesaran [66] combine the common correlated effects (CCE) estimation and the ARDL-based ECM model to form the so-called CS-ARDL approach.[2] This approach can deal with short- and long-run coefficients simultaneously, apart from addressing the aforementioned econometrics issues. Our primary model can be expressed as

$$\begin{aligned}\Delta co_{2i,t} =& \varphi_{0i} + \sum_{j=1}^{n} \varphi_{1ij} \Delta co_{2i,t-j} + \sum_{j=0}^{n} \varphi_{2ij}' \Delta x_{i,t-j} \\ &+ \sum_{j=0}^{n} \varphi_{3ij}' \Delta \bar{z}_{i,t-j} + u_{i,t}\end{aligned} \quad (4)$$

[2] The CS-ARDL estimation is performed with Stata 15 using the xtdcce2 command by Ditzen [23].

Table 3 Cross-sectional dependence and slope homogeneity tests

Dependence variable	Cross-sectional dependence			Slope homogeneity	
	Breusch–Pagan LM	Pesaran scaled LM	Pesaran CD	Delta	Adjusted delta
$\ln CO_2$	867.0***	1.721*	4.587***	14.19***	17.22***
lnY	928.3***	5.619***	10.57***	39.96***	48.42***
lnRE	810.6***	− 0.621	1.100	17.33***	21.03***
lnNRE	933.8***	4.997***	4.090***	7.16***	8.694***
lnTRD	1370***	26.57***	23.05***	11.41***	13.85***
lnFD	972.3***	7.010***	8.240***	12.72***	15.43***
lnURB	1090***	13.53***	3.837***	23.28***	28.25***

***, **, and *significant at 1%, 5%, and 10%, respectively

In Eq. (4), x represents the set of independent variables in Eq. (3) in logarithmic form, i.e., $x=(\ln Y, \ln Y^2, \ln RE, \ln NRE, \ln TRD, \ln FD, \ln URB)$. $\overline{z}$ denotes the average of all cross sections, i.e., $\overline{z} = (\Delta\overline{co}_2, \overline{x})$.

Panel causality test on the CS-ARDL model

The short-run Granger causality among the variables is obtained by employing the framework in Eq. (4) for all the remaining variables in vector x. Therefore, the CS-ARDL model for economic growth can be expressed as

$$\begin{aligned}\Delta y_{i,t} =& \gamma_{0i} + \sum_{j=1}^{n} \gamma_{1ij}\Delta y_{i,t-j} + \sum_{j=0}^{n} \gamma_{2ij}^{'}\Delta x_{i,t-j} \\ &+ \sum_{j=0}^{n} \gamma_{3ij}^{'}\Delta\overline{z}_{i,t-j} + u_{i,t}\end{aligned} \quad (5)$$

In Eq. (5), x is a vector consisting of CO_2, the share of renewable energy, the share of nonrenewable energy, trade openness, financial development, and urbanization, i.e., $x=(\ln CO_2, \ln RE, \ln NRE, \ln TRD, \ln FD, \ln URB)$, and z plays the same role as in Eq. (4).

The causality test between economic growth and CO_2 emissions is conducted using a pair of corresponding equations. The Wald test evaluates the null hypothesis in which the coefficients of economic growth in the equation of CO_2 emissions are simultaneously set at zero. In other words, the test is $\varphi_{2ij} = 0 \forall j$ in Eq. (4). The rejection of the null hypothesis implies that economic growth Granger causes CO_2 emissions in a unidirectional fashion. To examine whether CO_2 emissions Granger cause economic growth, we conduct the Wald test to determine the significance of the parameters, $\gamma_{2ij} = 0 \forall j$ in Eq. (5). The same procedure is used for every pair of variables in the system of equations to test for short-run Granger causality.

Table 4 Panel unit-root tests

Variable	CIPS statistics		CADF statistics	
	Level	1st difference	Level	1st difference
$\ln CO_2$	− 1.69	− 4.02***	− 2.5	− 3.26***
lnY	− 2.16**	− 2.76***	− 2.69***	− 2.37***
lnRE	− 2.41***	− 4.7***	− 2.75***	− 3.57***
lnNRE	− 1.48	− 4.25***	− 2.13	− 3.11***
lnTRD	− 1.85	− 3.33***	− 2.14	− 2.44***
lnFD	− 2.45***	− 4.16***	− 2.22	− 2.94***
lnURB	− 1.13	− 3.11***	− 1.84	− 2.69***

Intercept and trend variables are included in the CIPS and CADF tests. ***, **, and * significant at 1%, 5%, and 10%, respectively

Table 2 Summary statistics

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
$\ln CO_2$	922	2.035	0.522	0.269	3.312
lnY	922	10.19	0.718	8.458	11.63
lnRE	922	2.373	1.051	− 0.813	4.348
lnNRE	922	3.372	1.652	− 4.455	4.602
lnTRD	922	4.278	0.532	2.773	6.012
lnFD	922	− 1.372	0.714	− 6.226	0.000
lnURB	922	4.314	0.152	3.869	4.584

Table 5 Panel cointegration tests

Westerlund cointegration test	
Gt	− 3.523***
Ga	− 1.161
Pt	− 2.284**
Pa	− 1.244

*** and **significant at 1% and 5%

Table 6 Results of the EKC hypothesis on CO_2 emissions

Variables	(1) lnCO$_2$	(2) lnCO$_2$	(3) lnCO$_2$	(4) lnCO$_2$	(5) lnCO$_2$	(6) lnCO$_2$	(7) lnCO$_2$
lnY	2.758	− 1.290	− 6.441	3.86**	− 1.602	2.839	− 5.088
	(2.790)	(4.112)	(6.005)	(1.912)	(2.928)	(5.965)	(5.002)
lnY^2	− 13.188	2.864	31.233	− 19.06**	8.267	− 13.430	23.925
	(13.958)	(21.701)	(28.515)	(9.543)	(13.852)	(28.576)	(23.618)
lnRE	x	x	x	x	x	x	x
lnNRE	x	x	x	x	x	x	x
lnTRD	x	x			x	x	
lnFD	x		x		x		x
lnURB	x			x		x	x
Observations	848	848	848	848	848	848	848
R-squared	0.234	0.333	0.342	0.341	0.285	0.271	0.302
Number of groups	37	37	37	37	37	37	37

** and * significant at 5% and 10%, respectively. We use CS-ARDL(1,0,0,0,0,0,0,0). The independent variable is carbon dioxide, and the independent variables include income (Y), its squared term (Y^2), renewable energy (RE), nonrenewable energy (NRE), trade openness (TRD), financial development (FD), and urbanization (URB). Standard errors are in parentheses. "x" represents the inclusion of variables in the regression

Results

The analysis begins by confirming the existence of cross-sectional dependence and slope homogeneity in the panel. The test results are presented in Table 3. First, Breusch and Pagan's Lagrange multiplier (LM) test [67], the bias-adjusted LM test [68], and Pesaran's cross-sectional dependence (CD) test [69] all fail to reject the null hypothesis of no cross-sectional dependence. Second, the assumption that the slopes of estimates are homogeneous is violated, because the delta and adjusted delta statistics are both statistically significant. The results of these tests confirm the presence of cross-sectional dependence and slope homogeneity in the sample of OECD countries. As such, we consider the second-generation panel unit-root tests more appropriate for our analysis with respect to the OECD members.

The next step is to check whether the variables are stationary and cointegrated. Table 4 shows the CIPS and CADF tests regarding stationarity. The two panel unit-root tests yield similar results, except for Financial development. Economic growth and Renewable energy consumption are integrated at $I(0)$, whereas the remaining variables are $I(1)$. When it comes to cointegration, Table 5 presents the results from the error correction-based panel cointegration tests by Westerlund [70].[3] The group mean coefficient statistics (Gt and Pt) reject the null hypothesis of no cointegration, but the panel statistics (Ga and Pa) fail to do so. Thus, it is appropriate to conclude that a long-run relationship exists among the variables for OECD countries.

We test the validity of the EKC hypothesis on CO_2 emissions for OECD countries. We employ the CS-ARDL (1,0,0,0,0,0,0,0) model in which one lag term is added only to the independent variable.[4] Table 6 presents the result of several model specifications. Column 1 shows the long-run estimates with all explanatory variables (the share of consumption of renewable energy, the share of nonrenewable energy usage, trade openness, financial development, and urbanization). Although we retain the two energy variables, we add one component (trade openness, financial development, and urbanization) to models (3)–(6) and two components to models (5)–(7). Our empirical results fail to confirm the validity of the EKC hypothesis on CO_2 emissions for OECD countries in six out of the seven model specifications.

To examine the role of trade openness, financial development, and urbanization in the energy-growth-environment nexus in OECD countries, we examine the short- and long-run relationships simultaneously using the CS-ARDL model. The squared term of income (Y^2) is excluded, because the validity of the EKC hypothesis on CO_2 emissions cannot be confirmed. Our main empirical findings are presented in Table 7. The most striking feature is that the error correction terms (ECT) of all variables are negative and significant, highlighting the existence of their long-run interaction.

[3] The residual-based tests by Pedroni [84, 85] are performed to establish the validity of a cointegration relationship, though this method relies on first-generation macroeconometrics. The test results are not presented here, but are available upon request.

[4] We also run the CS-ARDL (1,1,1,1,1,1,1,1) model, in which the one-lag term is included in both the dependent and independent variables. The overall conclusions remain largely similar. The results are not presented here, but they are available upon request.

Table 7 Long- and short-run analytical results

Variable	ΔlnCO$_2$ (1)	Δln*Y* (2)	ΔlnRE (3)	ΔlnNRE (4)	ΔlnTRD (5)	ΔlnFD (6)	ΔlnURB (7)
Short-run effect							
ΔlnCO$_2$	–	0.144***	− 0.595***	0.810***	0.217*	− 0.034	− 0.312
		(0.034)	(0.201)	(0.245)	(0.120)	(0.203)	(0.242)
ΔlnY	0.549***	–	− 0.008	0.087	− 0.066	0.958	0.281
	(0.157)		(0.283)	(0.744)	(0.206)	(0.603)	(0.321)
ΔlnRE	− 0.228***	0.013	–	− 0.612	0.184***	− 0.274	− 0.092
	(0.055)	(0.028)		(0.540)	(0.054)	(0.409)	(0.089)
ΔlnNRE	0.253***	0.019	0.117	–	0.473**	0.040	0.020
	(0.078)	(0.075)	(0.764)		(0.226)	(0.151)	(0.107)
ΔlnTRD	0.142**	− 0.005	0.168	− 0.050	–	− 0.380**	− 0.244
	(0.062)	(0.031)	(0.195)	(0.240)		(0.170)	(0.199)
ΔlnFD	− 0.069	− 0.038	− 0.177*	− 0.168	0.019	–	0.137
	(0.067)	(0.024)	(0.099)	(0.127)	(0.073)		(0.204)
ΔlnURB	0.030	0.040	0.129	− 0.169	− 0.044	− 0.370*	–
	(0.037)	(0.033)	(0.142)	(0.121)	(0.039)	(0.216)	
Long-run effect							
lnCO$_2$	–	0.164***	− 0.839**	0.929***	0.298**	0.042	− 4.957
		(0.041)	(0.377)	(0.305)	(0.138)	(0.166)	(3.836)
lnY	0.489***	–	− 0.194	0.195	− 0.131	0.778	− 11.883
	(0.136)		(0.343)	(0.888)	(0.223)	(0.488)	(12.949)
lnRE	− 0.193***	0.017	–	− 0.448	0.210***	− 0.160	− 3.761*
	(0.049)	(0.031)		(0.663)	(0.061)	(0.324)	(2.179)
lnNRE	0.243***	− 0.006	1.592	–	0.442**	0.039	1.897
	(0.080)	(0.097)	(2.171)		(0.198)	(0.119)	(2.162)
lnTRD	0.124**	− 0.001	− 0.147	− 0.091	–	− 0.315**	7.445*
	(0.059)	(0.033)	(0.459)	(0.318)		(0.151)	(4.482)
lnFD	− 0.081	− 0.048	− 0.340	− 0.140	0.036	–	− 0.929
	(0.071)	(0.031)	(0.239)	(0.111)	(0.079)		(3.313)
lnURB	0.023	0.044	0.370	− 0.215	− 0.033	− 0.313	–
	(0.032)	(0.035)	(0.399)	(0.161)	(0.040)	(0.207)	
ECT	− 1.134***	− 0.956***	− 1.106***	− 1.087***	− 1.002***	− 1.177***	− 0.139***
	(0.041)	(0.036)	(0.050)	(0.057)	(0.035)	(0.049)	(0.044)
Observations	848	848	848	848	848	848	848
R-squared	0.315	0.372	0.406	0.275	0.468	0.564	0.122
Number of groups	37	37	37	37	37	37	37

***, **, and * significant at 1%, 5%, and 10%, respectively. Standard errors are in parentheses

Specifically, first, as presented in Columns 1 and 2 of Table 7, the estimated coefficients of the share of renewable energy and that of nonrenewable energy have different signs: the former is negative, whereas the latter is positive. This finding implies that the increased share of renewable energy mitigates CO_2 emissions, but the higher share of nonrenewable energy consumption is associated with a higher level of CO_2 emissions. In addition, their impact on economic growth is positive, though insignificant. We find that trade openness has a positive impact on CO_2 emissions, whereas financial development and urbanization play a limited role. Economic growth and CO_2 emissions are closely related, as their coefficients are highly significant in both the short and long runs.

Second, Columns 3 and 4 of Table 7 present the empirical findings concerning the share of renewable energy and the share of nonrenewable energy, showing that both of them are mainly driven by CO_2 emissions. The share of renewable energy consumption is negatively affected by the level of financial development in the short run, but the impact is insignificant in the long run. Neither trade openness nor urbanization affects the share of these energy sources.

Finally, the results presented in Columns 5, 6, and 7 of Table 7 confirm the short- and long-run impacts of the energy-growth-environment nexus on trade openness, financial development, and urbanization. In the long run, trade openness is driven by CO_2 emissions and energy consumption (whether the share of renewable energy or the share of nonrenewable energy sources). We find that economic activities are not linked to growth in trade openness, financial development, and urbanization. A higher level of CO_2 emissions increases trade openness but does not affect financial development and urbanization. We also find a negative impact of the share of renewable energy on urbanization in the long run. In summary, Table 7 provides a clear picture of the short- and long-run effects of trade activity, financial development, and urbanization on the energy-growth-environment nexus, as well as the impact in the reverse direction, the effect of the nexus on each variable.

We now examine the causal relationship among the variables based on the short- and long-run effects described above. The Wald causality tests are presented in Table 8. The key findings concerning long-run causality are as follows. First, CO_2 emissions bidirectionally Granger cause the share of renewable energy, the share of nonrenewable energy, and economic growth. Unidirectional Granger causality from the share of renewable energy to that of nonrenewable energy is found but not the opposite. Thus, we support the feedback hypothesis in the economic growth-CO_2 emissions nexus. Furthermore, we confirm the neutral hypothesis between economic growth and the share of renewable energy and nonrenewable energy consumption in the long run. As such, the achievement of sustainable development goals should be balanced among targeted economic growth, the shares of renewable and nonrenewable energy consumption, and CO_2 emissions.

Second, the share of renewable energy and CO_2 emissions are found to have bidirectional causality with trade openness, financial development, and urbanization. The finding emphasizes their importance in the increased share of renewable energy sources and the control over CO_2 emissions. Third, economic activities unidirectionally Granger cause financial development and urbanization, but there is no causality between economic activities and trade. Finally, we find bidirectional causality only between nonrenewable energy and urbanization. Figure 2 illustrates the observed effects of trade openness, financial development, and urbanization on the energy-growth-environment nexus.

Table 8 Long- and short-run Granger-causality results

Granger causality		Short run	Long run
ln*Y*ǂ	lnCO_2	12.22***	10.16***
lnREǂ	lnCO_2	17.11***	11.19***
lnNREǂ	lnCO_2	10.69***	12.61***
lnTRDǂ	lnCO_2	5.19**	6.91***
lnFDǂ	lnCO_2	1.07	7.13***
lnURBǂ	lnCO_2	0.65	5.56***
lnCO_2ǂ	ln*Y*	17.48***	9.3***
lnREǂ	ln*Y*	0.21	0.81
lnNREǂ	ln*Y*	0.06	0.84
lnTRDǂ	ln*Y*	0.03	0.79
lnFDǂ	ln*Y*	2.52	1.72
lnURBǂ	ln*Y*	1.49	1.51
lnCO_2ǂ	lnRE	8.81***	10.44***
ln*Y*ǂ	lnRE	0	2.27
lnNREǂ	lnRE	0.02	2.92*
lnTRDǂ	lnRE	0.74	2.24
lnFDǂ	lnRE	3.2*	5.03***
lnURBǂ	lnRE	10.44	3.67**
lnCO_2ǂ	lnNRE	10.56***	8.35***
ln*Y*ǂ	lnNRE	0.01	1.16
lnREǂ	lnNRE	1.29	1.64
lnTRDǂ	lnNRE	0.04	1.19
lnFDǂ	lnNRE	1.74	1.79
lnURBǂ	lnNRE	1.95	2.33*
lnCO_2ǂ	lnTRD	3.26*	1.94
ln*Y*ǂ	lnTRD	0.1	0.06
lnREǂ	lnTRD	11.63***	6.25***
lnNREǂ	lnTRD	4.38**	2.27
lnFDǂ	lnTRD	0.07	0.04
lnURBǂ	lnTRD	1.31	0.67
lnCO_2ǂ	lnFD	0.03	6.74***
ln*Y*ǂ	lnFD	2.53	7.17***
lnREǂ	lnFD	0.45	6.55***
lnNREǂ	lnFD	0.07	6.61***
lnTRDǂ	lnFD	4.98**	8.67***
lnURBǂ	lnFD	2.94*	7.66***
lnCO_2ǂ	lnURB	1.67	5.43***
ln*Y*ǂ	lnURB	0.76	5.06***
lnREǂ	lnURB	1.09	4.99***
lnNREǂ	lnURB	0.03	5.21***
lnTRDǂ	lnURB	1.51	5.31***
lnFDǂ	lnURB	0.45	4.89***

*** and ** significant at 1% and 5%. ǂ does not Granger cause

Regarding short-run causality, the causal directions in the energy-growth-environment nexus are similar to those in the long run. However, the causality of trade

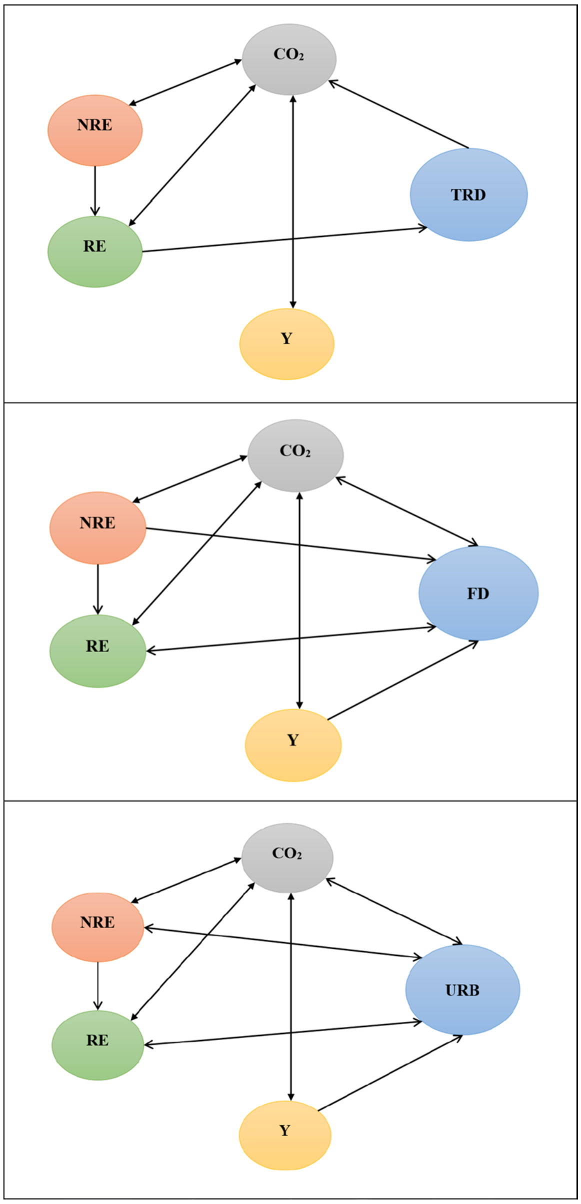

Fig. 2 Observed effects of trade openness, financial development, and urbanization on the energy-growth-environment nexus. See Fig. 1

openness, financial development, and urbanization in the nexus has a significant difference. We find only one-way causality from trade openness to CO_2 emissions and from the share of renewable energy sources to financial development.

Discussion

Our findings in this study reject the EKC hypothesis on CO_2 emissions in OECD countries. The same finding is obtained for the United States [8]. However, some scholars confirm this hypothesis for Latin American countries and developing economies [71, 72], China [38, 42, 59], some signatories to the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP) [5], and countries in Asia [73–75]. Regarding the energy-growth-environment nexus, our findings support contemporary empirical evidence on OECD members. Gozgor et al. [18] and Wang and Wang [76] confirm a positive link between renewable energy consumption and economic growth for a sample of 29 OECD countries over the period 1990–2013. Thus, we advocate a shift from the share of nonrenewable to the share of renewable energy use so that long-run sustainable development in both economic and environmental targets can be achieved. In contrast to Alvarado et al. [77], we document that it is not economic growth, but CO_2 emissions that affect the share of renewable and nonrenewable energy sources, implying that they are closely linked.

Trade openness increases CO_2 emissions. This finding is in line with earlier studies that assert trade openness has beneficial potential for reducing CO_2 emissions in the long run [15, 16, 57]. Interestingly, our findings support the technology effect on the environment and the pollution haven hypothesis on trade, implying that OECD countries are switching to industries that are more environmentally friendly. Our findings fail to confirm a positive relation between trade openness and the consumption share of renewable energy by OECD countries, unlike studies on diverse panels of countries [9, 78–81].

Financial development is found to have a negative impact on the share of renewable energy sources only in the short run. Our findings differ from other analyses that hold that increased financial development is associated with an increase in energy consumption and reduces CO_2 emissions in sub-Saharan African countries [46], European Union member countries [47], and Central and Eastern European frontier economies [48].

Urbanization increases CO_2 emissions and enhances economic growth, though its effect is insignificant. On one hand, our findings are consistent with those by Wand et al. [16], which confirm a positive link between urbanization and the environment in OECD countries. On the other hand, we strengthen the view that urbanization in OECD countries has reached a threshold at which the positive impact turns into a negative impact [82]. Moreover, our empirical findings regarding the impact of economic growth and urbanization on the share of renewable and nonrenewable energy sources are different from those of previous studies that support a positive impact using disaggregated energy usage by 29 OECD countries over the period 1980–2011 [83].

We also conducted additional analyses to check the robustness of our empirical findings. First, we use the CCE estimator to examine the validity of the EKC hypothesis on CO_2 emissions (Appendix Table 11) and reach the same conclusion. The hypothesis is mostly rejected, with only one confirmation involving urbanization in Eq. (3). Second, we use fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) estimators to check the long-run effects of all variables (Appendix Table 12). The long-run results in the FMOLS regression are relatively consistent with those in the CS-ARDL model in terms of coefficients' sign and significance. Finally, we check the robustness of the causality test using the vector error correction model (VECM), given the presence of a cointegrated relationship (Appendix Table 13). Some differences are found in the direction of causality between the VECM approach and the CS-ARDL model. We note that data used in this study suffer from both CD and slope heteroskedasticity issues, but the VECM approach fails to take these issues into account. Second, the VECM treats all variables as a simultaneous equations system whereas the CS-ARDL method treats every variable as a single equation. As such, we consider it more appropriate to use the CS-ARDL approach in our analysis.

Conclusions

The governments of the OECD member countries have ongoing concerns about increased demand for energy, which supports economic growth but also reduces environmental quality. Likewise, practitioners and scholars pay great attention to the different interactions among the share of renewable and nonrenewable energy sources, economic growth, and CO_2 emissions by OECD members, which account for a significant proportion of renewable energy supply and demand at the global level. We refer to the link of four variables as the energy-growth-environment nexus. Various theories support the potential role of trade openness, financial development, and urbanization on this nexus. As such, this study examines the interactive effects of the share of renewable and nonrenewable energy sources, economic growth, CO_2 emissions, trade openness, financial development, and urbanization in OECD member countries. Our findings offer important policy implications for OECD countries and for emerging markets to attain the demanding energy-growth-environment targets.

We find a long-run relationship among the variables when each of these variables of interest is used as the dependent variable. First, the validity of the EKC hypothesis on CO_2 emissions cannot be confirmed in this study despite its use of several model specifications. Second, the energy-growth-environment nexus documents the bidirectional causal relationship between CO_2 emissions and income as well as the share of both types of energy sources (renewable and nonrenewable) in the long run. These findings highlight the close relationship between economic growth, CO_2 emissions, and energy consumption. As such, a policy targeting one component needs to consider the impacts on the other components. For example, policies that target boosting economic growth should also consider an increase in energy demand and a deterioration in environmental quality. Conversely, policies that target reducing CO_2 emissions to achieve a sustainable development goal need to consider that in conjunction with economic growth and energy security. Another important finding is that the increased share of renewable energy is a long-term feasible measure for reducing environmental concerns in OCED countries. As such, strategies associated with an increase in the production and consumption of renewable energy sources should be encouraged and promoted. Finally, trade openness, financial development, and urbanization play different roles in the energy-growth-environment nexus. Whereas trade openness increases CO_2 emissions, financial development reduces the consumption share of renewable energy. Urbanization plays a limited role in this nexus in OECD countries.

These findings have potential policy implications. First, the OECD countries should increase the share of renewable energy sources by encouraging the adoption and use of more renewable energy, at the household and industry level. In addition, governments should drive efficient use of energy resources by promoting technological innovation, boosting efficient management, and fostering energy-efficient, clean environmental technologies. They should play an active role in boosting wind-based renewable energy, while giving financial assistance to reduce the fixed costs for setting up a solar power system.

Second, OECD governments should promote trade activities not only among their members but also with other countries for the purpose of sustainable economic development. They should target industries that rely on renewable energy sources and/or make environmentally friendly products. In addition, a regulatory framework should be constructed and implemented so as to shape environmental awareness by firms and across the government. Third, financial development has a short-term effect on the share of renewable energy consumption. As such, financial markets can serve as a channel for providing capital for investment in and expansion of business projects that are oriented toward technology and energy efficiency. Doing so will raise total factor productivity and optimize energy usage. Finally, our findings show the natural effect of urbanization on the energy-growth-environment nexus. The implication is that the state of urbanization in OECD members has no damaging effect on the achievement of the long-term plans for economic growth, the share of renewable and nonrenewable energy consumption, and the level of CO_2 emissions.

The study has some limitations. Apart from covering three important aspects in terms of general principals, CO_2 emissions does not appear to be a complete measure of environmental degradation. In addition, though we do our best to update the data scope, using a timeframe until 2015 and leaving out several years until the current year remain a downside of this research. Finally, we confirmed the role of trade openness and financial development on the nexus, but have yet to discover the potential mechanism and aforementioned hypothesis of these variables.

Addressing these limitations for the OECD countries offers a potential avenue for future research. Moreover, studies that analyze a sample of Asian and African countries are welcome because they have different patterns of financial development, trade openness, and urbanization. In addition, future studies should use a broader measure of environmental quality (i.e., the environment quality index) than CO_2 emissions, as is used in this paper.

Appendix

See Tables 9, 10, 11, 12, 13.

Table 9 Data sample

Country name	Period	Country name	Period
Australia	1990–2015	Latvia	1995–2015
Austria	1995–2015	Lithuania	1995–2015
Belgium	1991–2015	Luxembourg	1990–2015
Canada	1990–2015	Mexico	1990–2015
Chile	1990–2015	Netherlands	1990–2015
Colombia	1993–2015	New Zealand	1990–2015
Czech Republic	1992–2015	Norway	1990–2015
Denmark	1990–2015	Poland	1995–2015
Estonia	1993–2015	Portugal	1990–2015
Finland	1990–2015	Republic of Korea	1995–2015
France	1990–2015	Slovak Republic	1992–2015
Germany	1991–2015	Slovenia	1992–2015
Greece	1990–2015	Spain	1991–2015
Hungary	1990–2015	Sweden	1990–2015
Iceland	1990–2015	Switzerland	1990–2015
Ireland	1990–2015	Turkey	1990–2015
Israel	1990–2015	United Kingdom	1990–2015
Italy	1990–2015	United States	1990–2015
Japan	1990–2015		

Table 10 Correlation matrix

Variable	lnCO_2	ln*Y*	lnRE	lnNRE	lnTRD	lnFD	lnURB
lnCO_2	1						
ln*Y*	0.630	1					
lnRE	− 0.428	− 0.085	1				
lnNRE	0.145	− 0.229	− 0.575	1			
lnTRD	0.149	0.126	− 0.036	− 0.096	1		
lnFD	0.084	0.142	0.040	0.048	− 0.032	1	
lnURB	0.245	0.390	− 0.039	− 0.172	− 0.160	0.043	1

Table 11 Robustness check of EKC hypothesis with CCE estimators

Variables	(1) lnCO_2	(2) lnCO_2	(3) lnCO_2	(4) lnCO_2	(5) lnCO_2	(6) lnCO_2	(7) lnCO_2
ln*Y*	4.572	− 1.060	7.370	16.853*	2.240	3.175	10.465
	(5.678)	(7.499)	(5.519)	(9.925)	(5.469)	(8.100)	(7.264)
ln*Y*	− 0.205	0.075	− 0.316	− 0.780*	− 0.079	− 0.136	− 0.473
	(0.277)	(0.359)	(0.256)	(0.466)	(0.257)	(0.385)	(0.347)
lnRE	x	x	x	x	x	x	x
lnNRE	x	x	x	x	x	x	x
lnTRD	x	x			x	x	
lnFD	x		x		x		x
lnURB	x			x		x	x
Observations	922	922	922	922	922	922	922
Number of groups	37	37	37	37	37	37	37

See Table 6

Table 12 Robustness check of long-run effect with FMOLS and DOLS estimators

Variables	(1) lnCO_2	(2) ln*Y*	(3) lnRE	(4) lnNRE	(5) lnTRD	(6) lnFD	(7) lnURB
FMOLS estimation							
lnCO_2		0.177	− 1.07***	0.202***	0.839***	− 0.628	− 0.07***
		(0.112)	(0.320)	(0.048)	(0.253)	(0.421)	(0.022)
ln*Y*	0.552***		0.932*	0.114	− 1.73***	0.165	0.094***
	(0.131)		(0.503)	(0.072)	(0.387)	(0.658)	(0.017)
lnRE	− 0.25***	0.104**		0.003	0.702***	0.308*	0.008
	(0.033)	(0.045)		(0.020)	(0.095)	(0.171)	(0.010)
lnNRE	0.788***	0.721***	0.329		1.518***	− 1.142	− 0.008
	(0.187)	(0.239)	(0.750)		(0.529)	(0.904)	(0.050)
lnTRD	0.075**	0.005	0.204	0.060***		0.422**	0.024**
	(0.037)	(0.049)	(0.134)	(0.020)		(0.168)	(0.010)
lnFD	− 0.09***	− 0.026	0.425***	− 0.08***	0.036		− 0.05***
	(0.032)	(0.043)	(0.124)	(0.018)	(0.086)		(0.008)
lnURB	− 0.03***	0.045***	0.020	− 0.008*	0.099***	− 0.08***	
	(0.007)	(0.005)	(0.030)	(0.004)	(0.021)	(0.033)	
DOLS estimation							
lnCO_2		0.417	− 1.913**	0.334*	0.322	− 0.406	− 0.059
		(0.526)	(0.852)	(0.194)	(1.520)	(0.577)	(0.109)
ln*Y*	0.702*		1.976*	0.122	0.054	1.334*	0.135*
	(0.404)		(1.147)	(0.275)	(1.786)	(0.684)	(0.077)
lnRE	− 0.220*	0.117		0.018	0.577	0.348	− 0.002
	(0.120)	(0.217)		(0.086)	(0.528)	(0.215)	(0.048)
lnNRE	0.905	0.043	0.248		1.235	− 1.745	− 0.018
	(0.669)	(1.142)	(2.100)		(2.899)	(1.133)	(0.247)
lnTRD	− 0.114	0.035	− 0.038	− 0.017		− 0.038	0.026
	(0.158)	(0.257)	(0.433)	(0.102)		(0.266)	(0.044)
lnFD	− 0.082	0.021	0.117	− 0.005	− 0.011		− 0.026
	(0.155)	(0.206)	(0.406)	(0.089)	(0.627)		(0.037)
lnURB	− 0.018	0.041*	− 0.017	− 0.003	0.020	− 0.08***	
	(0.021)	(0.023)	(0.062)	(0.013)	(0.085)	(0.031)	

***, **, and * significant at 1 percent, 5 percent, and 10 percent, respectively. Standard errors are in parentheses

Table 13 Robustness check of the Granger causality with the VECM approach

Granger causality		Short-run
ln*Y*ǂ	lnCO_2	7.94***
lnREǂ	lnCO_2	3.52*
lnNREǂ	lnCO_2	0.5
lnTRDǂ	lnCO_2	2.99*
lnFDǂ	lnCO_2	4.67**
lnURBǂ	lnCO_2	2.01
lnCO_2ǂ	lnY	0.01
lnREǂ	lnY	0
lnNREǂ	lnY	1.49
lnTRDǂ	lnY	1.76
lnFDǂ	lnY	0.09
lnURBǂ	lnY	4.13**
lnCO_2ǂ	lnRE	0.43
ln*Y*ǂ	lnRE	9.73***
lnNREǂ	lnRE	0.08
lnTRDǂ	lnRE	0.03
lnFDǂ	lnRE	0.03
lnURBǂ	lnRE	0.67
lnCO_2ǂ	lnNRE	6.58**
ln*Y*ǂ	lnNRE	5.57**
lnREǂ	lnNRE	0.13
lnTRDǂ	lnNRE	0.64
lnFDǂ	lnNRE	1.76
lnURBǂ	lnNRE	0.17
lnCO_2ǂ	lnTRD	1.15
ln*Y*ǂ	lnTRD	8.69***
lnREǂ	lnTRD	1.15
lnNREǂ	lnTRD	0.98
lnFDǂ	lnTRD	0.84
lnURBǂ	lnTRD	0
lnCO_2ǂ	lnFD	4.74**
ln*Y*ǂ	lnFD	7.81***
lnREǂ	lnFD	0.91
lnNREǂ	lnFD	1.62
lnTRDǂ	lnFD	0
lnURBǂ	lnFD	0.12
lnCO_2ǂ	lnURB	0.09
ln*Y*ǂ	lnURB	1.22
lnREǂ	lnURB	2.74*
lnNREǂ	lnURB	0.07
lnTRDǂ	lnURB	0.02
lnFDǂ	lnURB	0.04

*** and ** significant at 1% and 5%, respectively. ǂDoes not Granger cause

Abbreviations

BRICS: Brazil, Russia, India, China, and South Africa; CCE: Common correlated effects; CD: Cross-sectional dependence; CO_2: Carbon dioxide; CS-ARDL: Cross-sectional augmented distributed lag; DOLS: Dynamic ordinary least squares; ECM: Error correction model; EKC: Environmental Kuznets curve; FD: Financial development; FMOLS: Fully modified ordinary least squares; LM: Lagrange multiplier; GDP: Gross domestic product; NRE: Nonrenewable energy; OECD: Organization for Economic Cooperation and Development; RE: Renewable energy; STIRPAT: Stochastic impacts by regression on population, affluence, and technology; TRD: Trade openness; TWh: Terawatt-hours; VECM: Vector ECM; URB: Urbanization.

Acknowledgements

We thank the anonymous participants at Vietnam's Conference on Business, Economics and Resources (Ho Chi Minh City Open University, Ho Chi Minh City, Vietnam, November 25–26, 2021) for their helpful suggestions. In addition, the manuscript was significantly improved by comments from Paul Mittelstädt and six anonymous referees. The final version was professionally edited by Debra Soled at Academic Editorial Services, California, USA. The authors acknowledge financial support from Ho Chi Minh City Open University under Grant E2021.03.1. The authors are solely responsible for any remaining errors or shortcomings.

Author contributions

Substantial contributions to the conception, design of the work, analysis, and drafting of the paper. All authors have read and approved the final manuscript.

Funding

This study is funded by Ho Chi Minh Open University, under Grant E2021.03.1.

Availability of data and materials

The data sets used in the current study are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Research Centre in Business, Economics & Resources, Ho Chi Minh City Open University, 97 Vo Van Tan Street, District 3, Ho Chi Minh City, Vietnam. [2]Office of Cooperation & Research Management, Ho Chi Minh City Open University, Ho Chi Minh City, Vietnam.

Received: 15 February 2022 Accepted: 8 November 2022
Published online: 08 December 2022

References

1. Li J, Zhang X, Ali S, Khan Z (2020) Eco-innovation and energy productivity: new determinants of renewable energy consumption. J Environ Manage 271:111028
2. Bashir MF, MA B, Hussain HI, et al (2022) Evaluating environmental commitments to COP21 and the role of economic complexity, renewable energy, financial development, urbanization, and energy innovation: Empirical evidence from the RCEP countries. Renew Energy 184:541–550
3. IEA (2020) Key World Energy Statistics 2020. Int Energy Agency 33:4649
4. Cihat K, Setareh K, Salih K (2021) The role of financial efficiency in renewable energy demand: evidence from OECD countries. J Environ Manage 285:112122
5. Vo DH, Vo AT, Ho CM, Nguyen HM (2020) The role of renewable energy, alternative and nuclear energy in mitigating carbon emissions in the CPTPP countries. Renew Energy 161:278–292
6. Vo DH, Vo AT (2021) Renewable energy and population growth for sustainable development in the Southeast Asian countries. Energy Sustain Soc 11:1–15

7. Ozturk I, Acaravci A (2013) The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. Energy Econ 36:262–267
8. Dogan E, Turkekul B (2016) CO2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. Environ Sci Pollut Res 23:1203–1213
9. Al-Mulali U, Ozturk I, Lean HH (2015) The influence of economic growth, urbanization, trade openness, financial development, and renewable energy on pollution in Europe. Nat Hazards 79:621–644
10. Dogru T, Bulut U, Kocak E et al (2020) The nexus between tourism, economic growth, renewable energy consumption, and carbon dioxide emissions: contemporary evidence from OECD countries. Environ Sci Pollut Res 27:40930–40948
11. Saidi K, Omri A (2020) Reducing CO2 emissions in OECD countries: do renewable and nuclear energy matter? Prog Nucl Energy 126:103425
12. Erdogan S, Okumus I, Guzel AE (2020) Revisiting the environmental Kuznets curve hypothesis in OECD countries: the role of renewable, non-renewable energy, and oil prices. Environ Sci Pollut Res 27:23655–23663
13. Ben M, Ben S, Ozturk I (2017) Testing environmental Kuznets curve hypothesis : the role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol Indic 60:824–831
14. Ahmad M, Wu Y (2022) Combined role of green productivity growth, economic globalization, and eco-innovation in achieving ecological sustainability for OECD economies. J Environ Manage 302:113980
15. Churchill SA, Inekwe J, Ivanovski K, Smyth R (2018) The environmental Kuznets curve in the OECD: 1870–2014. Energy Econ 75:389–399
16. Wang Y, Zhang X, Kubota J et al (2015) A semi-parametric panel data analysis on the urbanization-carbon emissions nexus for OECD countries. Renew Sustain Energy Rev 48:704–709
17. Gozgor G (2017) Does trade matter for carbon emissions in OECD countries? Evidence from a new trade openness measure. Environ Sci Pollut Res 24:27813–27821
18. Gozgor G, Lau CKM, Lu Z (2018) Energy consumption and economic growth: new evidence from the OECD countries. Energy 153:27–34
19. Ben M, Ben S, Ozturk I (2016) Testing environmental Kuznets curve hypothesis: the role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol Indic 60:824–831
20. Aydin M (2019) Renewable and non-renewable electricity consumption–economic growth nexus: evidence from OECD countries. Renew Energy 136:599–606
21. Kim S (2022) Economic growth, trade openness, and renewable energy on CO2 emissions in OECD countries. Energies 15:1–15
22. Zhang M, Zhang S, Lee CC, Zhou D (2021) Effects of trade openness on renewable energy consumption in OECD countries: new insights from panel smooth transition regression modelling. Energy Econ 104:105649
23. Ditzen J (2018) Estimating dynamic common-correlated effects in Stata. Stata J 18:585–617
24. Dogan E, Seker F (2016) The influence of real output, renewable and non-renewable energy, trade and financial development on carbon emissions in the top renewable energy countries. Renew Sustain Energy Rev 60:1074–1085
25. Waheed R, Sarwar S, Wei C (2019) The survey of economic growth, energy consumption and carbon emission. Energy Rep 5:1103–1115
26. Tiba S, Omri A (2017) Literature survey on the relationships between energy, environment and economic growth. Renew Sustain Energy Rev 69:1129–1146
27. Frankel JA, Romer D (1999) Does trade cause growth ? Am Econ Rev 89:379–399
28. Kim DH, Lin SC (2009) Trade and growth at different stages of economic development. J Dev Stud 45:1211–1224
29. Antweiler W, Copeland BR, Scott Taylor M (2001) Is free trade good for the environment? Am Econ Rev 91:887–908
30. Copeland BR, Taylor MS (2004) Trade, growth, and the environment. J Econ Lit 42:7–71
31. Wang X, Zhang C, Zhang Z (2019) Pollution haven or porter? The impact of environmental regulation on location choices of pollution-intensive firms in China. J Environ Manage 248:109248
32. Shahbaz M, Nasreen S, Ahmed K, Hammoudeh S (2017) Trade openness–carbon emissions nexus: the importance of turning points of trade openness for country panels. Energy Econ 61:221–232
33. Farhani S, Chaibi A, Rault C (2014) CO_2 emissions, output, energy consumption, and trade in Tunisia. Econ Model 38:426–434
34. Ghani GM (2012) Does trade liberalization effect energy consumption? Energy Policy 43:285–290
35. Sadorsky P (2011) Trade and energy consumption in the Middle East. Energy Econ 33:739–749
36. Sadorsky P (2012) Energy consumption, output and trade in South America. Energy Econ 34:476–488
37. Li M, Ahmad M, Fareed Z et al (2021) Role of trade openness, export diversification, and renewable electricity output in realizing carbon neutrality dream of China. J Environ Manage 297:113419
38. Ahmad M, Zhao ZY, Irfan M, Mukeshimana MC (2019) Empirics on influencing mechanisms among energy, finance, trade, environment, and economic growth: a heterogeneous dynamic panel data analysis of China. Environ Sci Pollut Res. 14148–14170.
39. Zeeshan M, Ullah I, Rehman A, Afridi FEA (2022) Trade openness and urbanization impact on renewable and non-renewable energy consumption in China. Environ Sci Pollut Res 29:41653–41668
40. Levine R, Levine R (1997) Financial development and economic growth: views and agenda. J Econ Lit 35:688–726
41. Fung MK (2009) Financial development and economic growth: convergence or divergence? J Int Money Financ 28:56–67
42. Ahmad M, Jabeen G, Hayat MK et al (2020) Revealing heterogeneous causal links among financial development, construction industry, energy use, and environmental quality across development levels. Environ Sci Pollut Res 27:4976–4996
43. Tamazian A, Rao BB (2010) Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. Energy Econ 32:137–145
44. Dasgupta S, Laplante B, Mamingi N (2001) Pollution and capital markets in developing countries. J Environ Econ Manage 42:310–335
45. Claessens S, Feijen E (2007) Financial sector development and the millennium development goals. World Bank Publications, Washington, DC
46. Acheampong AO (2019) Modelling for insight: does financial development improve environmental quality? Energy Econ 83:156–179
47. Çoban S, Topcu M (2013) The nexus between financial development and energy consumption in the EU: a dynamic panel data analysis. Energy Econ 39:81–88
48. Sadorsky P (2011) Financial development and energy consumption in Central and Eastern European frontier economies. Energy Policy 39:999–1006
49. Tamazian A, Chousa JP, Vadlamannati KC (2009) Does higher economic and financial development lead to environmental degradation: evidence from BRIC countries. Energy Policy 37:246–253
50. Zeeshan M, Han J, Rehman A et al (2021) Exploring determinants of financial system and environmental quality in high-income developed countries of the world: the demonstration of robust penal data estimation techniques. Environ Sci Pollut Res 28:61665–61680
51. Al Mamun M, Sohag K, Shahbaz M, Hammoudeh S (2018) Financial markets, innovations and cleaner energy production in OECD countries. Energy Econ 72:236–254
52. Qamruzzaman M, Jianguo W (2020) The asymmetric relationship between financial development, trade openness, foreign capital flows, and renewable energy consumption: fresh evidence from panel NARDL investigation. Renew Energy 159:827–842
53. Poumanyvong P, Kaneko S (2010) Does urbanization lead to less energy use and lower CO2 emissions? A cross-country analysis. Ecol Econ 70:434–444
54. Bloom DE, Canning D, Fink G (2008) Urbanization and the Wealth of Nations. Science 319(5864):772–775
55. Brückner M (2012) Economic growth, size of the agricultural sector, and urbanization in Africa. J Urban Econ 71:26–36
56. Henderson V (2003) The urbanization process and economic growth: the so-what question. J Econ Growth 8:47–71
57. Davis JC, Henderson JV (2003) Evidence on the political economy of the urbanization process. J Urban Econ 53:98–125
58. Zhang C, Lin Y (2012) Panel estimation for urbanization, energy consumption and CO 2 emissions: a regional analysis in China. Energy Policy 49:488–498

59. Ahmad M, Khan Z, Anser MK, Jabeen G (2021) Do rural-urban migration and industrial agglomeration mitigate the environmental degradation across China's regional development levels? Sustain Prod Consum 27:679–697
60. Dong K, Dong X, Jiang Q (2019) How renewable energy consumption lower global CO2 emissions? Evidence from countries with different income levels. World Econ 2017:1–34
61. Salim RA, Hassan K, Shafiei S (2014) Renewable and non-renewable energy consumption and economic activities: further evidence from OECD countries. Energy Econ 44:350–360
62. Wang Q, Su M, Li R, Ponce P (2019) The effects of energy prices, urbanization and economic growth on energy consumption per capita in 186 countries. J Clean Prod 225:1017–1032
63. Wang S, Li G, Fang C (2018) Urbanization, economic growth, energy consumption, and CO2 emissions: empirical evidence from countries with different income levels. Renew Sustain Energy Rev 81:2144–2159
64. Svirydzenka K (2016) Introducing a new broad-based index of financial development. IMF Work Pap 16:1
65. Chudik A, Pesaran MH (2015) Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. J Econom 188:393–420
66. Mtar K, Belazreg W (2021) On the nexus of innovation, trade openness, financial development and economic growth in European countries: new perspective from a GMM panel VAR approach. Int J Financ Econ. https://doi.org/10.1002/ijfe.2449
67. Breusch TS, Pagan AR (1979) A simple test for heteroscedasticity and random coefficient variation. Econometrica 47:1287–1294
68. Pesaran MH, Ullah A, Yamagata T (2008) A bias-adjusted LM test of error cross section independence. Econom J 11:105–127
69. Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econom 312:265–312
70. Westerlund J (2007) Testing for error correction in panel data. Oxf Bull Econ Stat 69:709–748
71. Ahmad M, Muslija A, Satrovic E (2021) Does economic prosperity lead to environmental sustainability in developing economies? Environmental Kuznets curve theory. Environ Sci Pollut Res 28:22588–22601
72. Alvarado R, Tillaguango B, Dagar V et al (2021) Ecological footprint, economic complexity and natural resources rents in Latin America: empirical evidence using quantile regressions. J Clean Prod 318:128585
73. Vo DH, Nguyen NT, Vo AT et al (2021) Does the Kuznets curve apply for financial development and environmental degradation in the Asia-Pacific region? Heliyon 7:e06708
74. To AH, Ha DTT, Nguyen HM, Vo DH (2019) The impact of foreign direct investment on environment degradation: evidence from emerging markets in Asia. Int J Environ Res Public Health 16:1636
75. Vo AT, Vo DH, Le QT-T (2019) CO2 emissions, energy consumption, and economic growth: new evidence in the ASEAN countries. J Risk Financ Manag 12:145
76. Wang Q, Wang L (2020) Renewable energy consumption and economic growth in OECD countries: a nonlinear panel data analysis. Energy 207:118200
77. Alvarado R, Deng Q, Tillaguango B et al (2021) Do economic development and human capital decrease non-renewable energy consumption? Evidence for OECD countries. Energy 215:119147
78. Dogan E, Seker F (2016) Determinants of CO2 emissions in the European Union: the role of renewable and non-renewable energy. Renew Energy 94:429–439
79. Omri A, Nguyen DK (2014) On the determinants of renewable energy consumption: international evidence. Energy 72:554–560
80. Sebri M, Ben-Salha O (2014) On the causal dynamics between economic growth, renewable energy consumption, CO2 emissions and trade openness: fresh evidence from BRICS countries. Renew Sustain Energy Rev 39:14–23
81. Pfeiffer B, Mulder P (2013) Explaining the diffusion of renewable energy technology in developing countries. Energy Econ 40:285–296
82. Dong F, Wang Y, Su B et al (2019) The process of peak CO2 emissions in developed economies: a perspective of industrialization and urbanization. Resour Conserv Recycl 141:61–75
83. Salim RA, Shafiei S (2014) Urbanization and renewable and non-renewable energy consumption in OECD countries: an empirical analysis. Econ Model 38:581–591
84. Pedroni P (1999) Critical values for cointegration tests in heterogeneous panels with multiple regressors. Oxf Bull Econ Stat 61:653–670
85. Pedroni P (2004) Panel cointegratoin: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econom Theory 20:597–625

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.