Environmental Science and Pollution Research (2021) 28:40917–40928
https://doi.org/10.1007/s11356-021-13613-2

RESEARCH ARTICLE

Investigating the dynamic linkages among carbon dioxide emissions, economic growth, and renewable and non-renewable energy consumption: evidence from developing countries

Dimitrios Dimitriadis[1] · Constantinos Katrakilidis[1] · Achillefs Karakotsios[1]

Received: 18 January 2021 / Accepted: 18 March 2021 / Published online: 27 March 2021

Abstract
This research paper examines the causal relationships among carbon dioxide emissions, economic growth, and renewable and non-renewable energy consumption, for a panel of 68 developing countries over the period 1990 − 2014. We use the multivariate panel cointegration framework and apply a battery of conventional (Pedroni 1999, 2004; and Kao 1999) as well as newly developed methodologies accounting for heterogeneity and cross-sectional correlation (Westerlund's ECM panel cointegration (2007) and panel bootstrap cointegration (2007) tests). The pooled mean group (PMG), mean group (MG), and dynamic fixed effects (DFE) methodologies were further applied to trace out the short-run dynamics. The results support evidence of significant dynamic linkages among the involved variables and reveal possible differences in the magnitude of the impacts from renewable and non-renewable energy consumption on environmental quality. The issue of distinguishing by source and determining the magnitude of the detected effects could provide valuable information for a sustainable economic and environmental development, substantially helping policy makers to designate more efficient policy measures.

Keywords Renewable energy consumption · Non-renewable energy consumption · Economic growth · Carbon dioxide emissions · Panel · Cointegration · Causality

Introduction

In recent years, environmental pollution and climate change gained particular attention from international institutions and policy makers, as well as from environmental and energy experts. Renewable energy sources are widely considered as a key factor for environmental recovery caused by the worldwide phenomenon of climate change and are expected to support the process toward sustainable development in the future (Kahia et al. 2017). The International Energy Outlook (2017) predicts that over the period 2015 – 2040, renewable energy will prove the fastest-growing source of electricity generation, rising by an average of 2.8% per year, and that in 2040, renewable sources will provide a share of the world's electricity generation comparable to that of coal, which is estimated at 31%. However, although renewable energy is considered the future source of energy, fossil fuels are expected to retain a large share of energy demand.

Bearing in mind the growing share of renewable energy consumption and its expected contribution to energy in the future, it becomes apparent why the distinction between renewable and non-renewable energy sources lies and probably will remain at the center of energy policies and certainly in the empirical research agenda. Although the relationship between energy consumption and economic growth has been thoroughly investigated in the past, only in the last few years has renewable energy consumption found its role in the relevant empirical literature (Apergis and Payne 2012).

So far, the empirical literature primarily focused on investigating causal effects within a bivariate econometric framework. Based on bivariate interactions, empirical studies have provided mixed results regarding the long-run impacts and the direction of the causality, particularly for the economic growth–energy consumption nexus (Hamit-Haggar 2016; Kula 2013; Apergis and Danuletiu 2014; Acaravci and Ozturk 2010; Menegaki 2011) and the economic growth–environmental degradation nexus (Magazzino 2017; Zoundi

---

Responsible editor: Nicholas Apergis

✉ Dimitrios Dimitriadis
dd_maths@hotmail.com

[1] Aristotle University of Thessaloniki, Thessaloniki, Greece

2017; Apergis and Ozturk 2015; Apergis and Payne 2009). It is only recently that a new strand of research has been developed, aiming at examining causal relationships within a multivariate framework and attempting to assess the impacts of energy consumption discriminating by source: that is, between non-renewable and renewable energy (Zrelli 2016; Dogan and Seker 2016; Zoundi 2017; Ito 2017).

However, the overall evidence remains inconclusive. Some empirical studies support that there is a negative causal effect running from renewable energy consumption to CO_2 emissions (Bekun et al. 2019; Jebli et al. 2020). On the other hand, a positive causal effect running from renewable energy consumption to CO_2 emissions is also reported (Thai-Ha Le et al. 2020). These mixed results might be attributed to the use of different groups of countries, such as Mediterranean countries, the European Union, and African countries, in addition to the different time periods and alternative econometric approaches (GMM, DOLS, PMG) used to capture possible causal effects. The above differentiations could probably justify the reports of mixed results and the consequent debate on the dynamic linkages among energy consumption, carbon dioxide emissions, and economic growth.

Consequently, this empirical effort contributes to the existing environment–energy–growth literature in four ways. First, it assesses the empirical link between economic growth, disaggregated by source of energy consumption (i.e., renewable and non-renewable), and environmental quality within a multivariate framework. This specific issue actually refers to the study of possible long-run causal impacts along with the direction of causality, which has not been extensively investigated. By distinguishing the effects of renewable and non-renewable energy consumption on environmental quality, we are able to assess the impacts of energy consumption by the source which is very important for policy designation. Second, given that 63% of annual carbon emissions is produced by developing countries, as reported by the Center for Global Development, this empirical effort attempts to provide a better and clearer insight by using an extended data set comprising 68 developing countries. Moreover, this paper adds to the debate by implementing newly developed panel econometric techniques to produce robust and reliable estimates accounting for heterogeneity among the cross-sections. The applied panel cointegration test accounts for interdependence between cross-sections with different individual effects. For the robustness of our results, the present study uses Westerlund's (2007) bootstrap test of panel cointegration to account for possible correlation between and within each one of the cross-sectional units. Besides, the pooled mean group (PMG) estimator provides heterogeneous, country-by-country, short-run coefficients and restricts the long-run coefficients as homogeneous across countries. Lastly, this effort contributes to the relevant empirical literature by setting under investigation the group of developing countries, since, for this particular group, there is a lack of relevant empirical researches, and more importantly, they are expected to follow a growth path in the future accompanied by a parallel increase in energy demand.

Our empirical results provide evidence of a long-run, positive, bi-directional, and causal relationship between economic growth and CO_2 emissions, as well as a positive, unidirectional causality running from renewable energy consumption to environmental quality. Non-renewable energy consumption appears to have a negative impact on environmental quality. More importantly, renewable and non-renewable energy consumption were both found to cause significant positive effects of equal magnitude on economic growth, which is an issue of special attention for policy makers. In the short run, we find evidence of causal effects running from CO_2 emissions to economic growth, while the impacts from both types of energy consumption on environmental quality are not significant. Our findings are of great importance for the tasks involved in economic policy making since they reveal that the joint goal of economic growth and environmental protection is probably feasible under appropriate reorientation and designation of the undertaken relevant policies.

The rest of the paper is structured as follows: "Review of the literature" provides a literature review of the energy consumption–economic growth–environmental quality nexus. "Methodological issues" provides a brief description of the employed econometric tools, while "Data and empirical results" reports on the construction and sources of the examined data sample and the findings from the empirical analysis. "Conclusions and policy implications" concludes the discussion.

Review of the literature

The relevant empirical literature can be distinguished in the following three categories: the relationship between economic growth and energy consumption, the relationship between energy consumption and environmental degradation, and finally, the relationship between economic growth and environmental degradation.

The economic growth–energy consumption nexus

The first strand of the literature is related to the economic growth–energy consumption nexus. Several empirical studies have been carried out during the last 30 years (Mutascu 2016; Dogan 2015; Dogan and Seker 2016; Farhani 2013), producing mixed empirical findings (Zrelli 2016). Four main hypotheses have been developed and examined in the literature according to the direction of the causal effects between economic growth and energy use, i.e., the growth, conservation, feedback, and neutrality hypotheses.

According to the growth hypothesis, energy consumption has a causal impact on economic growth. The hypothesis is valid when the empirical findings suggest that there is a unidirectional causality running from energy consumption to economic growth (Hamit-Haggar 2016). There are several empirical studies supporting the growth hypothesis. Inglesi-Lotz (2016) provided evidence in favor of the growth hypothesis for OECD countries, while Destek and Aslan (2017) provided the same evidence for 16 emerging economies. Moreover, Bowden and Payne (2010) used annual data from 1949 to 2006 for the USA and applied the Toda-Yamamoto causality method, providing evidence in favor of the growth hypothesis. The same evidence has been provided by Tiwari et al. (2015) by using annual data from 1971 to 2011 for 12 Sub-Saharan African countries.

By contrast, the conservation hypothesis asserts that economic growth affects energy consumption and holds if the one-way causality runs from economic growth to energy consumption (Kula 2013). The conservation hypothesis implies that energy policies focusing on the reduction of energy consumption will have no negative effect on economic growth. Aneja et al. (2017) used annual data for BRICS over the period 1990–2012 and applied the panel error correction modeling approach, finding evidence in favor of the conservation hypothesis.

The feedback hypothesis was supported when there is a bidirectional causal effect between energy consumption and economic growth (Apergis and Danuletiu 2014). There are also several studies providing evidence in favor of the feedback hypothesis for different time periods and different economies; in any case, the energy conservation policies designed to limit energy consumption will not have a negative impact on economic growth (Apergis and Payne 2011; Tugcu et al. 2012; Salim et al. 2014; Kahia et al. 2017; Aydin 2019).

Finally, according to the neutrality hypothesis, there is a lack of any causal relationship between energy consumption and economic growth. In this case, energy conservation policies will not affect economic growth (Payne 2009; Acaravci and Ozturk 2010; Menegaki 2011; Bhattacharya et al. 2016; Tuna and Tuna 2019).

The energy consumption–environmental quality nexus

The second strand of the literature is related to the energy consumption-environmental quality nexus. Several empirical studies concerning the relationship between energy consumption and environmental quality support the existence of a one-way causality running from energy use to environmental quality (Arouri et al. 2012; Omri 2013). If this is the case, a conservation energy policy may have a positive effect on the environment. The impact of energy consumption on environmental quality depends on the type of energy. For example, Shafiei and Salim (2014) argued that renewable energy consumption decreases CO_2 emissions, while non-renewable energy consumption increases them. Furthermore, Jebli et al. (2016) supported that in the long run, non-renewable energy consumption increases CO_2 emissions. Moreover, Asumadu-Sarkodie and Owusu (2017) proved that non-renewable energy consumption and industrialization may negatively affect environmental quality. Saboori et al. (2017) also provided evidence in favor of a positive causal effect running from oil consumption to CO_2 emissions. Bhat (2018) argued in favor of a positive causal effect from non-renewable energy consumption to CO_2 emissions as well as of a negative one running from renewable energy consumption to CO_2 emissions. Farhani and Shahbaz (2014) concluded with an interesting finding: They proved that an increase in renewable energy consumption may lead to accelerated environmental degradation by increasing CO_2 emissions. Khan and Hou (2021a) used FMOLS for 38 IEA countries for the period 1995–2018, supporting that energy consumption degrades environmental quality. Khan et al. (2021) used annual data for the USA over the period 1971–2016; using GMM, they found that non-renewable energy consumption may lead to a decrease in environmental quality.

The economic growth–environmental quality nexus

The third strand of the literature investigates the dynamic linkages between economic growth and environmental quality by testing the validity of the so-called Environmental Kuznets Curve ($EKC-$) hypothesis. Kuznets (1955) proposed a quadratic relationship between economic growth and environmental pollution; more specifically, he supported that there is an inverted "*U*"-shape relationship between real income per capita and environmental pollution. Despite the large number of empirical studies providing evidence in favor of the *EKC* hypothesis (Waqih et al. 2019; Pao and Chen 2019; Kiliç and Balan 2018; Tjoek and Wu 2018; Magazzino 2017; Zoundi 2017; Apergis and Ozturk 2015; Apergis and Payne 2009), the overall empirical evidence still provides rather mixed results. There is a group of empirical studies providing evidence in favor of a "*U*"-shape relationship between real income per capita and environmental degradation (Xu et al. 2020; Destek and Sinha 2020). There are also several studies which have found a monotonic increase of environmental pollution, while the real income per capita increases (Gui et al. 2019; Gorus and Aslan 2019; Ozcan et al. 2018). Finally, there is another group of empirical researches which rejects the *EKC* hypothesis by providing evidence in favor of an "*N*"-shape relationship between real income and environmental pollution (Allard et al. 2018; Halkos and Polemis 2017; Kang et al. 2016).

The economic growth–environmental quality–energy consumption nexus

Recently, a group of studies simultaneously examined the dynamic relationships among CO_2 emissions, renewable and non-renewable energy consumption, and economic growth. More specifically, Zrelli (2016) investigated the causal linkages between renewable and non-renewable energy consumption and economic growth, for a group of 14 Mediterranean countries over the period 1980 – 2011. The results of the generalized method of moment (*GMM*) dynamic model and the panel vector error correction model (VECM) they used support feedback between economic growth and renewable and non-renewable energy consumption in the short run and one-way causality, running from renewable energy consumption to economic growth in the long-run. Dogan and Seker (2016) investigated the impacts of renewable and non-renewable energy consumption, real income, and trade openness on CO_2 emissions, in the *EKC* model for the European Union over the period 1980 − 2012. The results of the dynamic ordinary least square (*DOLS*) estimator suggested that renewable energy consumption and trade have a negative impact on CO_2 emissions, while non-renewable energy consumption has a positive effect on environmental quality, and the existence of the *EKC* was supported. The results of the Dumitrescu and Hurlin (2012) panel causality test supported a two-way causality between renewable energy consumption and CO_2 emissions and a one-way causality running from CO_2 emissions to non-renewable energy consumption, from trade openness to CO_2 emissions, from real income to CO_2 emissions, and from real income to non-renewable energy consumption. Using pooled mean group models, Zoundi (2017) provided evidence that the *EKC* is not completely confirmed for the case of 25 selected African countries over the period 1980 − 2012. More specifically, the findings suggest that the *EKC* hypothesis is confirmed in the short run, while renewable energy consumption has a negative effect on CO_2 emissions with an increasing impact in the long-run. Ito (2017) empirically investigated the link between CO_2 emissions, economic growth, and renewable and non-renewable energy consumption for a group of 42 developing countries over the period 2002 − 2011. The results of the GMM and the *PMG* methodologies suggested that non-renewable energy consumption has a negative long-run impact on economic growth, whereas renewable energy consumption has a positive effect on economic growth in the long-run. In addition, renewable energy consumption was found to be negatively related to CO_2 emissions.

Mbarek et al. (2018) used panel VECM to examine four Mediterranean countries and found evidence in favor of a bi-directional causal effect between renewable energy consumption and economic growth, and a one-way causal effect running from CO_2 emissions to renewable energy consumption. Chen et al. (2019) used VECM for China and supported the existence of a one-way causal effect running from economic growth and CO_2 emissions to renewable energy consumption. In addition, Inglesi-Lotz and Dogan (2018) used Dumitrescu-Hurlin causality (Dumitrescu and Hurlin 2012) for Sub-Saharan African countries and provided evidence in favor of a two-way causal relationship between economic growth and environmental degradation, and a one-way causal effect running from CO_2 emissions to renewable energy consumption. Using annual data from 1980 to 2015 for the USA, Khan and Hou (2021b) showed that economic growth and capital formation may limit environmental quality, while renewable energy consumption improves it. They also provided evidence in favor of the *ECK* hypothesis. Using annual data from 1995 to 2018 for 30 IEA countries, Khan and Hou (2021c) proved that renewable energy consumption may lead to a decrease of CO_2 emissions and that there is a bi-directional positive causality between CO_2 emissions and economic growth.

Based on these mixed results, this study aims to fill the gap in the literature by examining both the economic and environmental impacts of renewable and non-renewable energy sources, by employing second-generation panel data methods to consider cross-sectional dependence among 68 developing countries.

Methodological issues

Cross-sectional dependence and panel unit root tests

Cross-sectional dependence may lead to forecasting errors and unreliable results. The existence of cross-sectional dependence is examined using Pesaran's CD-test (Pesaran 2004). Actually, Pesaran (2004) proposed the following test to examine for cross-sectional dependence:

$$CD=\sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right)\sim N(0,1) \tag{1}$$

where T is the panel's time dimension, N is the panel's cross-sectional dimension, and $\widehat{\rho}_{ij}$ is the fitted values of the pairwise correlation of the residuals.

Conventional first-generation unit root tests lose power if a strong and positive residual cross-sectional dependence exists. To overcome this issue, Pesaran (2007) proposed the cross-sectional augmented Dickey-Fuller (*CADF*) and the cross-sectional augmented Im, Pesaran, Shin (*CIPS*) unit root tests.

The *CADF* test extends the standard *DF* or *ADF* regressions by adding lagged cross-sectional means of the individual units and first differences. This test is based on the following regression:

$$\Delta y_{it} = a_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{j=0}^{p} d_{ij} \Delta \bar{y}_{t-j} + \sum_{j=0}^{p} f_{ij} \Delta y_{t-j} + u_{it} \quad (2)$$

where a_i is the constant term, $\bar{y}_{i,t-1}$ is the one lag value of the cross-sectional mean of $y_{i,\ t}$, and $\Delta \bar{y}_t$ are the first differences of $\bar{y}_t$. The optimal number of lags, p in Eq. (2), can be chosen according to the order of serial correlation in the error term (Pesaran 2007). For the present study, the optimal lag length was chosen based on the Schwarz Information Criterion (*SIC*). The *CIPS* test is estimated by the average of individual *CADF* statistics of the *i*-th cross-sectional units:

$$CIPS = \left(\frac{1}{N}\right) \sum_{t=1}^{N} CADF_i \ (3)$$

The null hypothesis, in both the *CADF* and *CIPS* tests, supports a homogeneous unit root across all individuals within a panel, whereas the alternative supports that there is at least one stationary individual in the panel.

Panel cointegration tests

Pedroni cointegration test

The Pedroni (1999, 2004) heterogeneous panel cointegration test allows for cross-section interdependence with different individual effects. In the first step of this procedure, the following relationship is estimated:

$$Y_{i,t} = a_{i,t} + \delta_i t + \sum_{j=1}^{m} \lambda_{ji} X_{i,t} + e_{i,t} \quad (4)$$

where $i = 1, \ldots, N$ refers to the cross-sections (countries) in the panel and $t = 1, \ldots, T$ refers to the time period, while coefficients $a_{i,\ t}$ and δ_i allow for country-specific fixed effects and deterministic trends, respectively. Deviations from the long-run equilibrium relationship are represented by the estimated residuals, $e_{i,\ t}$. In the next step, the following unit root test on the residuals is applied to test the null hypothesis of no cointegration:

$$e_{i,t} = \rho_i e_{i,t-1} + w_{i,t} \quad (5)$$

A result of $\rho_i = 1$ supports the null hypothesis of cointegration among the involved variables. Pedroni (1999, 2004) also develops asymptotic and finite-sample properties of the test statistics to examine the null hypothesis of no-cointegration in the panel. The slope coefficients λ_i are also permitted to vary by individual, so that in general, the cointegrating vectors may be heterogeneous across members of the panel. The tests allow for heterogeneity among individual members of the panel, including heterogeneity in both the long-run cointegrating vectors and in the dynamics, since there is no reason to believe that all parameters are the same across countries. Two types of tests are suggested by Pedroni (1999). The first type is based on the *within*-dimension approach and includes four statistics. They are the panel *v*-statistic, the panel *rho*-statistic, the panel *PP*-statistic, and the panel *ADF*-statistic. These statistics pool the autoregressive coefficients across different members for the unit root tests on the estimated residuals.

The second test by Pedroni (1999) is based on the *between*-dimension approach, which includes three statistics. They are the group *rho*-statistic, the group *PP*-statistic, and the group *ADF*-statistic. These statistics are based on estimators that simply average the individually estimated coefficients for each member. All seven tests are distributed as standard normal asymptotic distributions. This requires standardization based on the moments of the underlying Brownian motion function.

Kao cointegration test

The Kao cointegration test (1999) estimates the homogeneous cointegration relationship through pooled regression allowing for individual fixed effects. Kao (1999) proposed an *ADF* panel cointegration test where the vectors of cointegration are homogeneous. Let us consider $\widehat{e}_{i,t}$ as the estimated residual obtained from the following equation:

$$Y_{i,t} = a_i + \beta X_{i,t} + e_{i,t} \quad (6)$$

for all $t = 1, \ldots, T$ and $i = 1, \ldots, N$, where a_i and β are the parameters of the model. The *ADF* test is obtained by estimating the following regression:

$$e_{i,t} = \lambda e_{i,t-1} + \sum_{j=1}^{p} p_j \Delta \widehat{e}_{i,t-j} + v_{i,t} \quad (7)$$

where λ is chosen so that the residuals $v_{i,\ t}$ are serially uncorrelated assuming the null hypothesis of no-cointegration.

ECM panel cointegration test

Westerlund (2007) proposed a panel cointegration model (*ECM*) which is based on structural dynamics, in contrast to other residual–dynamics–based approaches. Westerlund proposed four basic panel cointegration tests under the null hypothesis of no cointegration (*Gt*, *Ga*, *Pt*, *Pa*) that offer *p*-values which are robust against cross-sectional dependencies using bootstrap methods. The *ECM* is given by the following form:

$$\Delta Y_{i,t} = \delta_{\iota}' d_t + a_i Y_{i,t-1} + \lambda_{\iota}' X_{i,t-1} + \sum_{j=1}^{p_i} a_{i,j} \Delta \Upsilon_{\iota,t-j} + \sum_{j=-q_i}^{p_i} \gamma_{i,j} X_{i,t-j} + e_{i,t} \tag{8}$$

where d_t represents the deterministic component and a_i determines the speed of adjustment to equilibrium after an unpredicted shock.

Bootstrap panel cointegration tests

Westerlund and Edgerton (2007) proposed a bootstrap test of panel cointegration under the null hypothesis of cointegration, using the Lagrange multiplier test of McCoskey and Kao (1998). This test accounts for possible correlation, both within and between the cross-sections, and can significantly reduce the distortions of the applied asymptotic test.

Long-run and short-run parameters estimation

The *PMG* estimator of Pesaran, Shin, and Smith (Pesaran et al. 1999) is an alternative to the autoregressive distributed lag (*ARDL*) cointegration approach for panel settings, which allows the intercepts, short-run coefficients, and cointegrating terms to differ across cross-sections.

Specifically, the *PMG* model can be written as:

$$\Delta Y_{i,t} = \varphi_i EC_{i,t} + \sum_{j=0}^{q-1} \Delta X_{i,t-j}' \beta_{i,j} + \sum_{j=1}^{p-1} \lambda_{i,j}{}^* \Delta Y_{i,t-j} + \epsilon_{i,t} \tag{9}$$

where

$$EC_{i,t} = Y_{i,t-1} - X_{i,t}' \theta \tag{10}$$

The *PMG* allows heterogeneous, country-by-country, short-run coefficients and homogeneous long-run coefficients across countries. However, a consistent *ARDL* model requires absence of autocorrelation in the residuals of the error correction model. Besides, the independent corresponding variables can be considered exogenous. When both *T* and *N* are large, we are allowed to use the dynamic panel technique to avoid bias in the average estimators and possible heterogeneity.

In cases where we have pooled time series data for each cross-section and the intercepts are allowed to vary across the cross-section units, the fixed effect (*FE*) model could be used. The *FE* approach may produce inconsistent and potentially misleading results when the slope coefficients are not identical. On the other hand, Pesaran and Smith (1995) proposed the mean group (*MG*) estimator, which could be fitted separately for each group and a simple arithmetic mean of the coefficients could be calculated. Individual regressions for each unit are estimated and the panel coefficients are calculated as unweighted means of the estimated coefficients for the individual cross-section units. Evidently, all coefficients can differ and be heterogeneous in both the long-run and short-run time horizon. The *MG* approach requires a large number of cross-section units *N* (more than 20) and a large number of time periods *T*, since with small *N*, the average *MG* estimators are quite sensitive to outliers and small model permutations (Favarra 2003).

Finally, with the dynamic fixed effects estimator (*DFE*), we obtain equal long-run slope coefficients and error variances across cross-section units. The short-run coefficients are equal across panel units too, while the intercepts can be country-specific. Baltagi et al. (2000) pointed out that with small data samples, the DFE model suffers from an endogeneity problem between the error term and the lagged dependent variable.

Data and empirical results

Our data source from the World Bank Database and comprise annual observations for 68 developing countries covering the period 1990 to 2014 (see Table 10 in Appendix A). This period is selected according to its full data set availability. The selection of the specific group of developing countries followed the relevant classification suggested by three international organizations, i.e., the International Monetary Fund (IMF), United Nations (UN), and World Bank (WB). More specifically, the obtained data series are the gross domestic product (*GDP*) per capita as a proxy of economic growth, the carbon dioxide (CO_2) emissions per capita as an indicator of environmental degradation, the fossil fuel energy consumption (*FFEC*), and the renewable energy consumption (*REEC*). A description of the collected data is presented in Table 1.

For the needs of the present study, *GDP* and CO_2 were used in logarithmic form, denoted by *LGDP* and LCO_2, respectively. Furthermore, the square of the logged *GDP* per capita (*LGDPSQ*) was calculated to account for a possible *EKC* type relation.

The first step in the empirical analysis examines the integration properties of the involved series. However, if a strong, positive, and significant cross-sectional dependence among residuals exists, the conventional estimation methods may provide inconsistent and unreliable results (Kapetanios et al. 2011). Consequently, we first apply a cross-sectional independence test, proposed by Pesaran (2004), in order to examine for a possible existence of cross-sectional dependence. The results are presented in Table 2.

Table 2 provides strong evidence in favor of the existence of residual cross-sectional dependence since the null hypothesis is rejected at the 5% level of significance; hence, we

Table 1 Data description

Abbreviation	Variable	Description
GDP	Gross domestic product per capita	In constant 2010 US$
CO_2	Carbon dioxide emissions per capita	In metric tons
FFEC	Fossil fuel energy consumption	As a percentage of total energy consumption
REEC	Renewable energy consumption	As a percentage of total energy consumption

proceed by applying two second-generation panel unit root tests which account for cross-sectional dependence.

In fact, we employ the CADF and the CIPS (Pesaran 2007) which are robust to the presence of dependence among cross-sections. The results in Table 3 support the existence of a unit root for all the involved variables in the levels but with stationarity in the first differences at the 1% level of significance. Thus, we can accept that all variables could be characterized as integrated of order one, *I*(1).

Note 1: Panel unit-root tests use intercept and time trend; the optimal lag length is chosen by SBC up to a maximum of two lags

Note 2: The critical values calculated for CIPS are −2.52, −2.58, and −2.69 for the 10%, 5%, and 1% levels of significance, respectively

Testing for possible cointegration, we firstly apply two conventional cointegration tests: the Pedroni (1999, 2004) heterogeneous panel cointegration test which allows for interdependence among cross-sections with different individual effects, and the Kao (1999) cointegration test which is an *ADF* panel cointegration test with homogeneous vectors of cointegration. Therefore, the Kao cointegration test (1999) estimates the homogeneous cointegration relationship using pooled regression, allowing for individual fixed effects. The results are reported in Table 4.

According to the results of the Pedroni cointegration test, we observe that four out of the seven statistics reject the null hypothesis of no cointegration. Following the evidence obtained from the majority of the above statistics, we could accept the existence of cointegration. It has to be mentioned that the Panel *ADF*, as well as the Group *ADF* statistic, which clearly support the existence of cointegration, may be considered more valid than the remaining statistics, especially in small samples (Lee and Chang 2008).

Table 2 Pesaran's cross-sectional independence test

	LGDP	*LGDPSQ*	LCO_2	*REEC*	*FFEC*
CD-test	163.79	160.74	44.15	21.23	11.26
p-value	0.000	0.000	0.000	0.000	0.000

Note: The CD-test is applied under the null hypothesis of cross-sectional independence

The last finding is further supported by the result of the KAO cointegration test which strongly rejects the null hypothesis of no cointegration. To check for the robustness of our previous finding, we further apply two more recent econometric tests: the error correction panel cointegration, and the panel bootstrap cointegration approaches, as suggested by Westerlund (2007).

The first cointegration test which is based on error correction models tests for cointegration by examining whether the individual panel units are error-correcting or not. This test is flexible and allows for the heterogeneous specification of the long-run and short-run terms of the error correction model, which can be considered data-driven. The obtained results can be shown in Table 5.

The results support the existence of cointegration among the involved variables since three out of four statistics are found to be statistically significant at the 5% level of significance.

The second test which is implemented in order to confirm the existence of cointegration is Westerlund's bootstrap cointegration test (Westerlund 2007). The existence of cross-sectional correlations may negatively affect the robustness of common cointegration tests. Using a bootstrap methodology, the results are free of cross-sectional dependencies and they can be considered valid. The results of the bootstrap test are reported in Table 6.

Table 3 Second-generation panel unit root tests

	Levels		First differences	
Variable	CADF (*p*-value)	CIPS	CADF (*p*-value)	CIPS
LGDP	−2.068 (0.986)	−2.301	−2.710 (0.000)	−3.900
LGDPSQ	−2.068 (0.984)	−2.219	−2.687 (0.000)	−3.857
LCO_2	−2.330 (0.990)	−2.508	−2.587 (0.005)	−4.894
REEC	−1.783 (1.000)	−2.243	−2.521 (0.009)	−4.619
FFEC	−1.752 (1.000)	−2.245	−3.609 (0.000)	−4.571

Table 4 Pedroni and KAO Cointegration tests

Panel test statistics		Group mean panel test statistics	
Pedroni cointegration test			
Panel *v*	−4.418 (1.000)	Group *rho*	5.000 (1.000)
Panel *rho*	1.991 (0.976)	Group *PP*	−17.034 (0.000)
Panel *PP*	−11.281 (0.000)	Group *ADF*	−8.398 (0.000)
Panel *ADF*	−8.084 (0.000)		
KAO cointegration test			
t-statistic	*p*-value		Result
−6.729	0.000		Cointegration

Note: Numbers in parentheses denote probability values

With the aim of determining the long and possible short-run causal effects from different energy sources on economic growth and environmental quality, we estimate the *PMG*, the *MG*, and the *DFE* models and compare their efficiency using Hausman's test (Hausman 1978). The results of Hausman's test are presented in Table 7.

As can be observed in Table 6, the *PMG* model is found to fit better to our dataset; hence, we base our inference on this specification. The long-run coefficients and the error correction term of the examined models are presented in Table 8.

The results reported above reveal a long-run causal effect running from the independent variables to the dependent ones; these are supported by the estimated error correction terms which are negative and statistically significant. More specifically, there is a positive long-run causal effect running from *LGDP* and *FFEC* to LCO_2, and a negative long-run causal effect running from *REEC* to *LCO2*. Since the coefficient of *LGDPSQ* is found statistically insignificant (p-value=0.325), the *EKC* hypothesis is not supported. From the same table, we further observe that there is a positive long-run causal effect running from LCO_2, *FFEC*, and *REEC* to *LGDP*. It is also important to mention that in the model with *LGDP* as the dependent variable, the coefficients of the *REEC* and *FFEC* variables reveal impacts of equal magnitude on the *LGDP*.

Table 5 Westerlund's ECM panel cointegration test

Statistic	Statistic value (Robust *p*-value)	Result
Gt	−2.580 (0.008)	Cointegration
Ga	−6.699 (0.043)	Cointegration
Pt	−16.180 (0.008)	Cointegration
Pa	−6.742 (0.108)	No cointegration

Note: Null hypothesis: no cointegration

Table 6 Westerlund's panel bootstrap cointegration test

Statistic	Statistic value (Bootstrapped *p*-value)	Result
LM	30.010 (0.701)	Cointegration

Note: Null hypothesis: cointegration; the test was applied with 10.000 bootstraps

The last step of our analysis concerns the detection of possible short-run causal effects among the included variables. The findings are presented in Table 9.

In Table 8, it is observed that the only significant short-run causal effect is running from LCO_2 to *LGDP*. Weak short-run causal effects are detected running from *LGDP* and from *LGDPSQ* to LCO_2.

Conclusions and policy implications

This paper examined the dynamic linkages among carbon dioxide emissions, economic growth, and renewable and non-renewable energy consumption for a panel of 68 developing countries over the period 1990 − 2014. For this reason, complementary to conventional methodologies, we applied newly developed bootstrap tests of panel cointegration to establish the presence of cointegration and subsequently to produce robust and reliable estimates allowing for heterogeneity across developing countries.

Our results revealed the existence of a positive bi-directional causal relationship between economic growth and carbon dioxide emissions, as well as significant causal effects running from renewable and non-renewable energy sources to environmental quality. These effects have opposite signs, indicating the importance of distinguishing the different impacts of renewable and non-renewable energy consumption on environmental quality.

Our findings can be summarized as follows: In the long-run horizon, the *PMG* model results provided evidence of a positive long-run causal effect running from both economic growth and non-renewable energy consumption to environmental quality and a negative long-run causal effect running from renewable energy consumption to environmental

Table 7 Hausman's test

Null hypothesis	Alternative hypothesis	*p*-value	Result/suggestion
PMG	*MG*	0.942	*PMG*
DFE	*MG*	1.000	*DFE*
PMG	*DFE*	1.000	*PMG*

Table 8 Long-run coefficients and error correction term from PMG

Dependent variable	Independent variables	ARDL model	Long-run coefficients (p-value)				Error correction term (p-value)	Result
LCO_2	$LGDP$, $LGPDSQ$, $FFEC$, $REEC$	(1,1,1,1,1)	0.918 (0.009)	−0.021 (0.325)	0.012 (0.000)	−0.012 (0.000)	−0.479 (0.000)	Long-run causality
$LGDP$	LCO_2, $FFEC$, $REEC$	(1,1,1,1)	0.048 (0.002)	0.010 (0.000)	0.010 (0.000)	–	−0.228 (0.000)	Long-run causality

quality. The existence of the *EKC* is not supported. Furthermore, renewable and non-renewable energy sources, as well as carbon dioxide emissions, were found to cause positive impacts on economic growth. Our evidence is in line with the findings of Ito (2017) for a group of 42 developing countries, with regard to the positive effect of renewable energy consumption on economic growth, and the negative effect on CO_2 emissions. The above negative causal relationship is also in agreement with the results of Dogan and Seker (2016) and Zoundi (2017) for the European Union and for a group of 25 selected African countries, respectively.

Regarding the short-run time horizon, a causal relationship was found running from carbon dioxide emissions to economic growth, while weak causal effects were detected running from the opposite direction. Moreover, a lack of significant short-run causal effects from both the considered energy sources on environmental quality has also been confirmed.

Regarding the policy implications, the findings of our research clearly indicate that there is a negative causal relationship running from renewable energy consumption to CO_2 emissions. Consequently, the reduction of non-renewable energy consumption is the rational solution to ensure environmental sustainability. However, especially for emerging countries, this solution can be detrimental for their economic growth (Destek and Aslan 2017). The above assumptions lead to the sensible conclusion that when developing countries are designating their energy and environmental policies, they should lay emphasis on increasing renewable energy consumption despite the economic consequences.

Hence, the policy makers of developing countries have the difficult task of proceeding to a fair and much needed balance between economic growth and sustainability policies. More specifically, the empirical evidence shows that increased economic activity may lead to an increase of CO_2 emissions. Nevertheless, at the expense of economic growth, the competent authorities such as energy commissions and governmental agencies are expected to achieve a growing share of renewable energy to accomplish lower levels of CO_2 emissions.

However, the obtained findings point towards an optimistic direction without the absolute condemnation of the possibility of economic growth. More specifically, according to the above-mentioned findings, the estimated long-run coefficients of renewable and non-renewable energy consumption are of the same magnitude, albeit with opposite signs. Hence, it is arguable that the policies designed to provide incentives for increasing renewable energy consumption might have a dual simultaneous positive outcome: on the one hand, environmental degradation will inevitably be reduced; on the other hand, the negative effects on economic development will be avoided. All in all, a win–win situation is a viable possibility so long as developing countries decide to modify the energy consumption mix in favor of renewable energy sources.

The aforementioned conclusion is supported by Apergis and Ozturk (2015), who reaffirm that economic growth is not necessarily sacrificed on the altar of the adoption of environmental degradation measures.

Taking into consideration that both energy consumption sources have been found to be growth friendly, a critical question that arises concerns the options of developing countries with no or limited access to the market of renewable energy. Obviously, in such cases, the adoption and development of environmentally–friendly policies, in combination with the enactment of mechanisms which increase the use of renewable energy sources, is the best possible solution.

Table 9 Short-run causalities

Dependent variable	Independent variables	Short-run effects (p-value)				Result
LCO_2	$LGDP$, $LGPDSQ$, $FFEC$, $REEC$	(0.095)	(0.085)	(0.328)	(0.322)	No short-run causality
$LGDP$	LCO_2, $FFEC$, $REEC$	(0.001)	(0.382)	(0.348)	–	Short-run causality

Appendix

Table 10 Sixty-eight country panel

Albania
Algeria
Angola Argentina Armenia Azerbaijan
Bangladesh Belarus
Benin
Bolivia Botswana
Brazil
Bulgaria Cameroon
China
Colombia
Congo

Costa Rica Dominican Republic Ecuador
Egypt
El Salvador
Ethiopia
Gabon
Georgia
Ghana
Guatemala Honduras
Hungary
India
Indonesia
Iran
Iraq
Jamaica

Jordan
Kazakhstan
Kenya
Lebanon
Malaysia
Mexico
Mongolia
Morocco
Nepal
Nigeria
North Macedonia
Pakistan
Panama
Paraguay
Peru
Philippines
Poland

Romania
Russia
Saudi Arabia
Senegal
South Africa
Sudan
Thailand
Tunisia
Turkey
Ukraine
United Arab Emirates
Uruguay
Uzbekistan
Venezuela
Vietnam
Zambia
Zimbabwe

Availability of data and materials The dataset used during the current study is available from the corresponding author on reasonable request. Data has been retrieved from https://data.worldbank.org/data-catalog/world-development-indicators

Author contribution DD drafted the manuscript, CK guided the econometrics analysis and revised it, and AK was a major contributor in writing the literature review of the manuscript. All authors read and approved the final manuscript.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Acaravci A, Ozturk I (2010) Electricity consumption-growth nexus: evidence from panel data for transition countries. Energy Econ 32(3): 604–608. https://doi.org/10.1016/j.eneco.2009.10.016

Allard A, Takman J, Uddin GS, Ahmed A (2018) The N-shaped environmental Kuznets curve: an empirical evaluation using panel quantile regression approach. Environ Sci Pollut Res 25:5848–5861. https://doi.org/10.1007/s11356-017-0907-0

Aneja R, Banday UJ, Hasnat T, Koçoglu M (2017) Renewable and non-renewable energy consumption and economic growth: empirical evidence from panel error correction model. Jindal J Bus Res 6(1): 76–85. https://doi.org/10.1177/2278682117713577

Apergis N, Danuletiu DC (2014) Renewable energy and economic growth: evidence from the sign of panel long-run causality. Int J Energy Econ Policy 4(4):578–587

Apergis N, Ozturk I (2015) Testing Environmental Kuznets Curve hypothesis in Asian countries. Ecol Indic 52:16–22. https://doi.org/10.1016/j.ecolind.2014.11.026

Apergis N, Payne J (2009) CO_2 emissions, energy usage, and output in Central America. Energy Policy 37(8):3282–3286. https://doi.org/10.1016/j.enpol.2009.03.048

Apergis N, Payne J (2011) Renewable and non-renewable electricity consumption-growth nexus: evidence from emerging market economies. Appl Energy 88(12):5226–5230. https://doi.org/10.1016/j.apenergy.2011.06.041

Apergis N, Payne J (2012) Renewable and non-renewable energy consumption-growth nexus: evidence from a panel error correction model. Energy Econ 34(3):733–738. https://doi.org/10.1016/j.eneco.2011.04.007

Arouri M, Ben Youssef A, M'henni H, Rault C (2012) Energy consumption, economic growth and $C0_2$ emissions in Middle East and North African countries. Energy Policy 45:342–349. https://doi.org/10.1016/j.enpol.2012.02.042

Asumadu-Sarkodie S, Owusu PA (2017) A multivariate analysis of carbon dioxide emissions, electricity consumption, economic growth, financial development, industrialization, and urbanization in Senegal. Energy Sourc Part B Econ Plann Policy 12(1):77–84. https://doi.org/10.1080/15567249.2016.1227886

Aydin M (2019) Renewable and non-renewable electricity consumption-economic growth nexus: evidence from OECD countries. Renew Energy 136:599–606. https://doi.org/10.1016/j.renene.2019.01.008

Baltagi B, Griffin J, Xiong W (2000) To pool or not to pool: homogeneous versus heterogeneous estimators applied to cigarette demand. Rev Econ Stat 82(1):117–126. https://doi.org/10.1162/003465300558551

Bekun F, Alola A, Sarkodie S (2019) Toward a sustainable environment: nexus between $C0_2$ emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. Sci Total Environ 657:1023–1029. https://doi.org/10.1016/j.scitotenv.2018.12.104

Bhat JA (2018) Renewable and non-renewable energy consumption-impact on economic growth and $C0_2$ emissions in five emerging market economies. Environ Sci Pollut Res 25(35):35515–35530. https://doi.org/10.1007/s11356-018-3523-8

Bhattacharya M, Baramati SR, Ozturk I, Bhattacharya S (2016) The effect of renewable energy consumption on economic growth: evidence from top 38 countries. Appl Energy 162:733–741. https://doi.org/10.1016/j.apenergy.2015.10.104

Bowden N, Payne J (2010) Sectoral analysis of the causal relationship between renewable and non-renewable energy consumption and real output in the U.S. Energy Sourc B 5:400–408. https://doi.org/10.1080/15567240802534250

Chen Y, Wang Z, Zhong Z (2019) $C0_2$ emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. Renew Energy 131:208–216. https://doi.org/10.1016/j.renene.2018.07.047

Department of Energy (2017) The International Energy Outlook. Energy Information Administration, U.S, Washington, DC

Destek MA, Aslan A (2017) Renewable and non-renewable energy consumption and economic growth in emerging economies: evidence from bootstrap panel causality. Renew Energy 111:757–763. https://doi.org/10.1016/j.renene.2017.05.008

Destek MA, Sinha A (2020) Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: evidence from organization for economic cooperation and development countries. J Clean Prod 242:118537. https://doi.org/10.1016/j.jclepro.2019.118537

Dogan E (2015) The relationship between economic growth and electricity consumption from renewable and non-renewable sources: a study of Turkey. Renew Sust Energ Rev 52:534–546. https://doi.org/10.1016/j.rser.2015.07.130

Dogan E, Seker F (2016) Determinants of $C0_2$ emissions in the European Union: the role of renewable and non-renewable energy. Renew Energy 94:429–439. https://doi.org/10.1016/j.renene.2016.03.078

Dumitrescu E, Hurlin C (2012) Testing for Granger non-causality in heterogeneous panels. Econ Model 29(4):1450–1460. https://doi.org/10.1016/j.econmod.2012.02.014

Farhani S (2013) Renewable energy consumption, economic growth and $C0_2$ emissions: evidence from selected MENA countries. Energy Econo Lett 1:24–41

Farhani S, Shahbaz M (2014) What role of renewable and non-renewable electricity consumption and output is needed to initially mitigate $C0_2$ emissions in MENA region? Renew Sust Energ Rev 40:80–90. https://doi.org/10.1016/j.rser.2014.07.170

Favarra G (2003) An empirical reassessment of the relationship between finance and growth. IMF Working Papers 03(123):1

Gorus MS, Aslan M (2019) Impact of economic indicators on environmental degradation: evidence from MENA countries. Renew Sust Energ Rev 103:259–268. https://doi.org/10.1016/j.rser.2018.12.042

Gui S, Zhao L, Zhang Z (2019) Does municipal solid waste generation in China support the environmental Kuznets curve? New evidence from spatial linkage Analysis. Waste Manag 26(8):1162–1180. https://doi.org/10.1016/j.wasman.2018.12.006

Halkos GE, Polemis ML (2017) Does financial development affect environmental degradation? Evidence from the OECD countries. Bus Strateg Environ 26(8):1162–1180. https://doi.org/10.1002/bse.1976

Hamit-Haggar M (2016) Clean energy-growth nexus in sub-Saharan Africa: evidence from cross-sectionally dependent heterogeneous panel with structural breaks. Renew Sust Energ Rev 57:1237–1244. https://doi.org/10.1016/j.rser.2015.12.161

Hausman J (1978) Specification tests in econometrics. Econometrica 46(6):1251. https://doi.org/10.2307/1913827

Inglesi-Lotz R (2016) The impact of renewable energy consumption to economic growth: a panel data application. Energy Econ 53:58–63. https://doi.org/10.1016/j.eneco.2015.01.003

Inglesi-Lotz R, Dogan E (2018) The role of renewable versus non-renewable energy to the level of $C0_2$ emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. Renew Energy 123:36–43. https://doi.org/10.1016/j.renene.2018.02.041

Ito K (2017) $C0_2$ emissions, renewable and non-renewable energy consumption, and economic growth: evidence from panel data for developing countries. Int Econ 151:1–6. https://doi.org/10.1016/j.inteco.2017.02.001

Jebli BM, Youssef BS, 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. https://doi.org/10.1016/j.ecolind.2015.08.031

Jebli BM, Farhani S, Guesmi K (2020) Renewable energy, $C0_2$ emissions and value added: empirical evidence from countries with different income levels. Struct Chang Econ Dyn 53:402–410. https://doi.org/10.1016/j.strueco.2019.12.009

Kahia M, Aïssa M, Lanouar C (2017) Renewable and non-renewable energy use–economic growth nexus: the case of MENA Net Oil Importing Countries. Renew Sust Energ Rev 71:127–140. https://doi.org/10.1016/j.rser.2017.01.010

Kang YQ, Zhao T, Yang YY (2016) Environmental Kuznets curve for $C0_2$ emissions in China: a spatial panel data approach. Ecol Indic 63:231–239. https://doi.org/10.1016/j.ecolind.2015.12.011

Kao C (1999) Spurious regression and residual-based tests for cointegration in panel data. J Econ 90(1):1–44. https://doi.org/10.1016/S0304-4076(98)00023-2

Kapetanios G, Pesaran M, Yamagata T (2011) Panels with non-stationary multifactor error structures. J Econ 160(2):326–348. https://doi.org/10.1016/j.jeconom.2010.10.001

Khan I, Hou F (2021a) The dynamic links among energy consumption, tourism growth, and the ecological footprint: the role of environmental quality in 38 IEA countries. Environ Sci Pollut Res 28:5049–5062. https://doi.org/10.1007/s11356-020-10861-6

Khan I, Hou F (2021b) Does multilateral environmental diplomacy improve environmental quality?The case of the United States. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-12005-2

Khan I, Hou F (2021c) The impact of socio-economic and environmental sustainability on $C0_2$ emissions: a novel framework for thirty IEA countries. Soc Indic Res. https://doi.org/10.1007/s11205-021-02629-3

Khan I, Hou F, Le HP (2021) The impact of natural resources, energy consumption, and population growth on environmental quality: fresh evidence from the United States of America. Sci Total Environ 754. https://doi.org/10.1016/j.scitotenv.2020.142222

Kiliç C, Balan F (2018) Is there an environmental Kuznets inverted-U shaped curve? Panoeconomicus 65(1):79–94. https://doi.org/10.2298/PAN150215006K

Kula F (2013) The long-run relationship between renewable electricity consumption and GDP: evidence from panel data. Energy Sourc Part B Econ Plann Policy 9(2):156–160. https://doi.org/10.1080/15567249.2010.481655

Kuznets S (1955) Economic growth and income inequality. Am Econ Rev 45:1–28

Le T, Chang Y, Park D (2020) Renewable and non-renewable energy consumption, economic growth, and emissions: international evidence. Energy J 41(2):73–92. https://doi.org/10.5547/01956574.41.2.thle

Lee C, Chang C (2008) Energy consumption and economic growth in Asian economies: a more comprehensive analysis using panel data. Resour Energy Econ 30(1):50–65. https://doi.org/10.1016/j.reseneeco.2007.03.003

Magazzino C (2017) The relationship among economic growth, $C0_2$ emissions, and energy use in the APEC countries: a panel VAR approach. Environ Syst Decis 37(3):353–366. https://doi.org/10.1007/s10669-017-9626-9

Mbarek MB, Saidi K, Feki R (2018) How effective are renewable energy in addition of economic growth and curbing CO2 emissions in the long run? A panel data analysis for four Mediterranean countries. J Knowl Econ 9(3):754–766. https://doi.org/10.1007/s13132-016-0365-9

McCoskey S, Kao C (1998) A residual-based test of the null of cointegration in panel data. Econ Rev 17(1):57–84. https://doi.org/10.1080/07474939808800403

Menegaki A (2011) Growth and renewable energy in Europe: a random effect model with evidence for neutrality hypothesis. Energy Econ 33(2):257–263. https://doi.org/10.1016/j.eneco.2010.10.004

Mutascu M (2016) A bootstrap panel Granger causality analysis of energy consumption and economic growth in the G7 countries. Renew Sust Energ Rev 63:166–171. https://doi.org/10.1016/j.rser.2016.05.055

Omri A (2013) $C0_2$ emissions, energy consumption and economic growth nexus in MENA countries: evidence from simultaneous equations models. Energy Econ 40:657–664. https://doi.org/10.1016/j.eneco.2013.09.003

Ozcan B, Apergis N, Shahbaz M (2018) A revisit of the environmental Kuznets curve hypothesis for Turkey: new evidence from bootstrap rolling window causality. Environ Sci Pollut Res 25(32):32281–32394. https://doi.org/10.1007/s11356-018-3165-x

Pao HT, Chen CC (2019) Decoupling strategies: $C0_2$ emissions, energy resources, and economic growth in the Group of Twenty. J Clean Prod 206:907–919. https://doi.org/10.1016/j.jclepro.2018.09.190

Payne J (2009) On the dynamics of energy consumption and output in the US. Appl Energy 86(4):575–577. https://doi.org/10.1016/j.apenergy.2008.07.003

Pedroni P (1999) Critical values for cointegration tests in heterogeneous panels with multiple regressors. Oxf Bull Econ Stat 61(s1):653–670. https://doi.org/10.1111/1468-0084.0610s1653

Pedroni P (2004) Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econometr Theory 20(03):597–625

Pesaran M (2004) General diagnostic test for cross section dependence in panels. Cambridge Working Papers in Economics 35 Faculty of Economics, University of Cambridge.

Pesaran M (2007) A simple panel unit root test in the presence of cross-section dependence. J Appl Econ 22(2):265–312. https://doi.org/10.1002/jae.951

Pesaran M, Smith R (1995) Estimating long-run relationships from dynamic heterogeneous panels. J Econ 68(1):79–113. https://doi.org/10.1016/0304-4076(94)01644-F

Pesaran M, Shin Y, Smith R (1999) Pooled mean group estimation of dynamic heterogeneous panels. J Am Stat Assoc 94(446):621–634

Saboori B, Rasoulinezhad E, Sung J (2017) The nexus of oil consumption, $C0_2$ emissions and economic growth in China, Japan and South Korea. Environ Sci Pollut Res 24(8):7436–7455. https://doi.org/10.1007/s11356-017-8428-4

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. https://doi.org/10.1016/j.eneco.2014.05.001

Shafiei S, Salim R (2014) Non-renewable and renewable energy consumption and $C0_2$ emissions in OECD countries: a comparative analysis. Energy Policy 66:547–556. https://doi.org/10.1016/j.enpol.2013.10.064

Tiwari AK, Apergis N, Olayeni OR (2015) Renewable and nonrenewable energy production and economic growth in sub-Saharan Africa: a hidden cointegration analysis. Appl Econ 47(9):861–882. https://doi.org/10.1080/00036846.2014.982855

Tjoek P, Wu P (2018) Exploring the environmental Kuznets curve for CO2 and SO2 for Southeast Asia in the 21st century context. Environ Econ 9(1):7–21

Tugcu CT, Ozturk I, Aslan A (2012) Renewable and non-renewable energy consumption and economic growth relationship revisited: evidence from G7 countries. Energy Econ 34:1942–1950. https://doi.org/10.1016/j.eneco.2012.08.021

Tuna G, Tuna VE (2019) The asymmetric causal relationship between renewable and non-renewable energy consumption and economic growth in the ASEAN-5 countries. Res Policy 62:114–124. https://doi.org/10.1016/j.resourpol.2019.03.010

Waqih MAU, Bhutto NA, Ghumro NH, Kumar S, Salam MA (2019) Rising environmental degradation and impact of foreign direct investment: an empirical evidence from SAARC region. J Environ Manag 243:472–480. https://doi.org/10.1016/j.jenvman.2019.05.001

Westerlund J (2007) Error-correction-based cointegration tests for panel data. Stata J 8(2):232–241. https://doi.org/10.1177/1536867X0800800205

Westerlund J, Edgerton D (2007) A panel bootstrap cointegration test. Econ Lett 97(3):185–190. https://doi.org/10.1016/j.econlet.2007.03.003

Xu C, Yiwen Z, Cheng B, Li L, Zhang M (2020) Study on environmental Kuznets curve for noise pollution: a case of 111 Chinese cities. Sustain Cities Soc 63:102493. https://doi.org/10.1016/j.scs.2020.102493

Zoundi Z (2017) $C0_2$ emissions, renewable energy and the environmental Kuznets curve, a panel cointegration approach. Renew Sust Energ Rev 72:1067–1075. https://doi.org/10.1016/j.rser.2016.10.018

Zrelli M (2016) Renewable energy, non-renewable energy, carbon dioxide emissions and economic growth in selected Mediterranean countries. Environ Econ Policy Stud 19(4):691–709. https://doi.org/10.1007/s10018-016-0170-5