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ORIGINAL PAPER

The four-way linkages between renewable energy, environmental quality, trade and economic growth: a comparative analysis between high and middle-income countries

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Abstract This paper examines the four-way interrelationship between renewable energy, environment, foreign trade and growth using simultaneous-equation panel data models for 24 middle- and high-income countries over the period 1990–2011. Our findings show that, for the high-income countries, there is a bidirectional causality between renewable energy and growth, between CO_2 emissions and economic growth, between foreign trade and growth and between renewable energy and CO_2 emissions. However, there is a unidirectional causality between foreign trade and renewable energy and between emissions and trade. In the case of middle-income countries, there is also a bidirectional causality between renewable energy and growth, between CO_2 emissions and growth, between trade and growth, between trade and renewable energy and between CO_2 emissions and trade. On the other hand, there is a unidirectional causality, running from renewable energy to CO_2 emissions. Understanding these controversial scenarios is prerequisite to reaching an international agreement on climate change in order to build sound economic policies and improving the environmental quality to sustain economic development.

Keywords Renewable energy · Environmental quality · Trade · Economic growth

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1 Introduction

The relationship between energy consumption and economic growth have been widely examined in the literature of economic energy (e.g. [13,18,23,26,31,36,40,55,67]). In addition, these previous studies are based on the Granger causality tests which are widely used in order to investigate the direction of causality. However, their results have been characterized by the lack of paradoxical consensus. This paradox of economic energy literature has been explained largely through the omission bias of important variables, which affects the interaction between energy consumption and economic growth.

The omission bias, which means the elimination of relevant variables, consists in the main reason for more recent studies based on the Granger causality tests to investigate the causality relationship between energy consumption and economic growth including other important variables, such as capital, labor (e.g. [6,7,28,37,63,68,70,71]). Moreover, a more recent paper has included trade, as a relevant variable (e.g. [37,48,63]) whose studies aim at examining the causality relationship between energy consumption and economic growth.

Nevertheless, the dynamic interaction between energy consumption, trade and economic growth has been well studied in the past few decades, which it has been the topic of many debates and academic researches that belong to the economic energy field. Based on the environmental Kuznets curve (EKC) literature, the interaction between economic growth and energy consumption may generate weigh heavily on the environmental quality (e.g. [3,8,10,16,30,34,35,38,69,72,76]). Hence, the interaction between economic growth and pollutant emissions conforms with an inverted-U shape, which is consistent with the EKC hypothesis, which states that as economic growth increases, carbon dioxide increase. When threshold level of growth is reached, these emissions begin to decline. Indeed, the expansion of production causes more energy consumption, which puts pressure on the environmental quality leading to more pollutant emissions. This implies the degradation of the environment, which will later have a causal impact on economic growth, and also a persistent decline in the environmental quality which may exert a negative externality to economic growth through the health violations affecting human health, and consequently it may cause the reduction of productivity in the long run. The negative externality caused by the pollutant emissions has not only a negative impact on economic growth via reducing productivity, but also on the pollutant emissions which can be the main reason of the increase of the greenhouse gas and consequently it can be the booster of global warming. Therefore, it is crucial to apply some sorts of pollution control actions and drastic energy conservation measure such as the adoption of renewable and clean energy. This latter has been the subject of several academic researches and political debates (e.g. [11,12,14,19,21,24,25,44,59,62,64,75,77]).

The aim of this study is to investigate the impact of renewable energy consumption on economic growth and on carbon dioxide emissions. In other words, renewable energy can boost economic growth and/or mitigate pollutant emissions. This study offers the opportunity to better decide the ability of renewable energy in order to solve the gap: arbitration between economic growth and environmental quality by using simultaneous-equation models. Compared to previous studies, we use a simultaneous-equation modeling approach to investigate the impact of renewable energy consumption on economic growth and on carbon dioxide emissions in a framework of four-way linkages between renewable energy consumption, CO_2 emissions, trade openness, and economic growth. In the literature, there is no study which has investigated this relationship using simultaneous equation models procedure. Compared to the above existing literature our paper thus contributes in the two following ways: First we employ a simultaneous equation models approach in order to investigate the four-way linkages between renewable energy consumption, carbon dioxide emissions, trade, and economic growth. This modeling approach relies on the GMM-estimator and helps us simultaneously examine the following combined causality effects of: (1) CO_2 emissions, renewable energy consumption and trade openness on economic growth, (2) economic growth, renewable energy consumption and trade on CO_2 emissions, (3) economic growth, CO_2 emissions and trade openness on renewable energy consumption, and (4) economic growth, CO_2 emissions and renewable energy consumption on trade openness.

The remainder of this paper is organized as follows: Sect. 2 outlines the materials of the modeling frame work. Section 3 contains the results. Section 4 discussions the empirical findings, and Sect. 5 concludes the paper and shows the policy implication.

2 Methods and materials

2.1 Econometric modeling

The aim of this paper is to examine the ability of renewable energy to mitigate pollutant emissions and keep a sustainable economic growth in the case of four-way interrelationships between renewable energy consumption carbon dioxide emissions, trade, and economic growth in a comparative framework between middle-and high-income countries using annual data over the period of 1990–2011. In fact, these four variables are endogenous. As often mentioned, there is an impressive body of existing literature where it is generally suppose that, as income increases, CO_2 emissions increase but at some threshold of income is reached, pollutants emissions begin to decline according to the environmental Kuznets curve (EKC), which supports that economic growth would likely lead to changes in CO_2 emissions. In addition, it was established that renewable energy consumption plays a vital role in determining the CO_2 emissions. Moreover, the crucial role of trade in accelerating the adoption of renewable energy, which is linked to the transfer of technology, means that an indirect effect may exist in the short term from trade openness to renewable energy consumption through technology transfer [19,62] examined the causal relationship between economic growth, renewable energy consumption and CO_2 emissions. It is therefore worth investigating the interrelationship between the four variables by simultaneously considering them in a modeling framework.

For this purpose, we use the Cobb–Douglas production function to analyze the four-way linkages between renewable energy consumption, CO_2 emissions, trade openness and economic growth, such as capital and labor as additional factor of production [4,70,73], among others, included energy consumption, CO_2 emissions and trade openness variables in their empirical model to examine the impact of these variables on economic growth. Thus, our proposed model, which is consistent with the broader literature on the determinants of economic growth cited above; takes the following form:

$$\mathrm{Y} = \mathrm{A}R\mathrm{E}^{\alpha_1} C^{\alpha_2} \mathrm{T}^{\alpha_3} K^{\alpha_4} L^{\alpha_5} e^{\mu} \tag{1}$$

The logarithmic transformation of Eq. (1) form with a time series specification is given by:

$$\ln(Y_t) = \alpha_0 + \alpha_1 \ln(RE_t) + \alpha_2 \ln(C_t) + \alpha_3 \ln(T_t) + \alpha_4 \ln(K_t) + \alpha_5 \ln(L_i) + \mu_t \tag{2}$$

We then divide both sides of Eq. (4) by L to get variables in per capita terms; but leave the impact of labor constant, Eq. (2) can be specified as follows:

$$\ln(Y_t) = \alpha_0 + \alpha_1 \ln(RE_t) + \alpha_2 \ln(C_t) + \alpha_3 \ln(T_t) + \alpha_4 \ln(K_t) + \mu_t \tag{3}$$

Since our study is a panel data study, Eq. (3) can be rewritten in panel data form as follows:

$$\ln(Y_{it}) = \alpha_0 + \alpha_{1i} \ln(RE_{it}) + \alpha_{2i} \ln(C_{it}) + \alpha_{3i} \ln(T_{it}) + \alpha_{4i} \ln(K_{it}) + \mu_{it} \tag{4}$$

where: $\alpha_0 = \ln(\mathrm{A}_0)$; the subscript i = 1,…, N denotes the country (in our study, we have 24 countries) and t = 1,…, T denotes the time period (our time frame is 1990–2011). Variable Y is the per capita real GDP; RE, C, T and K denote per capita renewable energy consumption (RE), per capita CO_2 emissions (C), the trade openness (T) and the capital stock (K), respectively. As well as financial development (FD) measured as total credit of the private sector as a share of GDP that, it is introduced such as a determinant variable of the level of CO_2 emissions [56,71]. A is the level of technology and e is the residual term assumed to be identically, independently and normally distributed. The returns of scale are associated with, renewable energy consumption, CO_2 emissions and trade openness and capital are shown by α_1, α_2, α_3 and α_4, respectively which we have a constant returns of scale ($\sum_{i=1}^{4} \alpha_i = 1$). The logarithmic transformation aims at linearizing the form of the non linear Cobb–Douglas production function. It should be noted that simple linear specification does not seem to provide consistent results. Therefore, to overcome this problem, we use the log-linear specification to investigate the interrelationship between economic growth, renewable energy consumption, trade and CO_2 emissions in 24 countries divided into two sub-panels based on the level of income.

The four-way linkages between these variables are empirically examined by making use of the following four simultaneous equations:

$$\ln(GDP_{it}) = \alpha_0 + \alpha_{1i} \ln(RE_{it}) + \alpha_{2i} \ln(C_{it}) + \alpha_{3i} \ln(T_{it}) + \alpha_{4i} \ln(K_{it}) + \mu_{it} \tag{5}$$

$$\ln(RE_{it}) = \xi_0 + \xi_{1i}\ln(GDP_{it}) + \xi_{2i}\ln(C_{it}) + \xi_{3i}\ln(T_{it}) + \xi_{4i}\ln(OP_{it}) + \xi_{5i}\ln(OC_{it}) + \varepsilon_{it} \quad (6)$$

$$\ln(\mathrm{CO}_{2it}) = \varphi_0 + \varphi_{1i}\ln(GDP_{it}) + \varphi_{2i}\ln(RE_{it}) + \varphi_{3i}\ln(T_{it}) + \varphi_{4i}\ln(URB_{it}) + \varphi_{5i}\ln(FD) + \lambda_{it} \quad (7)$$

$$\ln(T_{it}) = \psi_0 + \psi_{1i}\ln(GDP_{it}) + \psi_{2i}\ln(RE_{it}) + \psi_{3i}\ln(C_{it}) + \psi_{4i}\ln(FDI_{it}) + \pi_{it} \quad (8)$$

In the above equations, the subscript $i = 1, ..., N$ denotes the country and $t = 1, ..., T$ denotes the time period.

Equation (5) states the impact of renewable energy consumption (RE), CO_2 emissions (C) and capital stock (K) where we take gross fixed capital formation as a proxy that can potentially determine economic growth (e.g. [4,5,9,10, 38,45,48,63]). Equation (6) postulates that real GDP (GDP), CO_2 emissions (C), trade (T) and other variables namely oil price (OP) and oil consumption can potentially affect renewable energy consumption (e.g. [9,10,14,19,37,48,62,63]). Equation (7) suggests that real GDP (GDP), renewable energy consumption (RE), trade (T), urbanization degree (URB) and financial development can potentially affect CO_2 emissions (e.g. [32,41,43,64]). Equation (8) reveals that real GDP (GDP), renewable energy consumption (RE), CO_2 emissions (C), and other variables, namely foreign direct investment (FDI) can potentially affect trade openness (e.g. [32,35,46,56,71]).

Equations (5), (6), (7), (8) were simultaneously estimated by means of the generalized method of moments (GMM). The GMM is the estimation method most commonly used in models with panel data and in the multiple-way linkages between certain variables. This method uses a set of instrumental variables to solve the endogeneity problem.

2.2 The estimation procedure

2.2.1 Panel unit root testing

We begin our framework by performing the panel unit root test proposed by (LLC) [42] and (IPS) [33]. Both of LLC and IPS are based on the Augmented Dickey–Fuller principle.

Levin et al. [42] considered the following basic Augmented Dickey–Fuller model:

$$\Delta y_{i,t} = \alpha_i + \beta_i y_{i,t-1} + \sum_{j=1}^{p_i} \mu_{i,j}\, \Delta y_{i,t-j} + \varepsilon_{i,t} \quad (9)$$

where Δ is the first difference operator,$X_{i,t}$ is the dependent variable i over period t, and the $\varepsilon_{i,t}$ is a white-noise disturbance with a variance of σ_i^2. Both $\beta_i$and the lag order μ in Eq. (9) are permitted to vary across sections (countries). Hence, they assumed

$$\begin{cases} \beta_i = 0 \\ \beta_i \prec 0; \end{cases}$$

where the alternative hypothesis corresponds to $Y_{i,t}$ being stationary.

According to the LLC test, compared with the single-equation Augmented Dickey–Fuller test, the panel method sensibly raises power in finite samples. The proposed model is as follows:

$$\Delta Y_{i,t} = \alpha_i + \beta Y_{i,t-1} + \sum_{j=1}^{P_i} \mu_{i,j} \Delta Y_{i,t-j} + \varepsilon_{i,t}. \tag{10}$$

Accordingly, [42] also assumed

$$\begin{cases} H_0 : \beta_1 = \beta_2 = ... = \beta = 0 \\ H_1 : \beta 1 = \beta_2 = ... = \beta \prec 0 \end{cases};$$

where the statistic of test is $t_\beta = \frac{\widehat{\beta}}{\sigma(\widehat{\beta})}$, $\widehat{\beta}$ is the OLS estimate of β in Eq. (10) and $\sigma(\widehat{\beta})$is its standard error.

Im et al. [33] proposed a testing procedure based on the mean group approach. The starting point of the *IPS test* is also the ADF regressions given in Eq. (10). However, the null and alternative hypotheses are different from that of the LLC test, where the rejection of the null hypothesis implies that all the series are stationary. We now have

H_0: $\beta_1 = \beta_2 = \ldots = \beta_N = 0$ vs. H_1: Some but not necessarily all $\beta_i \prec 0$

The IPS test is calculated as the average of the t-statistic with and without trend. Alternative t-bar statistics for testing the null hypothesis of unit root for all individuals ($\beta_i = 0$) is as follows

$$\bar{t} = \frac{\sum_{i=1}^{N} t\beta_i}{N} \tag{11}$$

where t is the estimated Augmented Dickey–Fuller statistics from individual panel members; N is the number of individuals. Using Monte Carlo simulations, this test shows that the t-bar ($\bar{t}$) is normally distributed under the null hypothesis. Accordingly, it then used estimates of its mean and variance to convert t-bar ($\bar{t}$) into a standard normal z-bar ($\bar{z}$) statistics which is given by:

$$\bar{z} = \frac{\sqrt{N}\,(\bar{t} - E[\bar{t}|\beta_i = 0])}{\sqrt{var[\bar{t}|\beta_i = 0]}} \rightarrow N(0, 1) \tag{12}$$

where $E[\bar{t}|\beta_i = 0]$ and $var[\bar{t}|\beta_i = 0]$ are the mean and variance of t_{it}. Moreover, the IPS study shows that the standardized statistics converges weakly to the standard normal distribution, which allows for comparison with critical values of the distribution N (0, 1).

2.2.2 The estimation techniques

It is well-known that the GMM method provides consistent and efficient estimates in the presence of arbitrary heteroskedasticity. Moreover, most of the diagnostic tests discussed in this study can be cast in a GMM framework. The GMM is the estimation method most commonly used in models with panel data and in the multiple-way linkages between certain variables. This method uses a set of instrumental variables to solve the endogeneity problem. Moreover, most of the diagnostic tests discussed in this study can be cast in a GMM framework. In addition, before running the regressions, some specific tests have been audited. According to [50,74], two important specification tests are used for simultaneous-equation regression models: test of endogeneity/exogeneity and test of overidentifying restrictions. First, the Durbin–Wu–Hausman (DWH) test was used to test the endogeneity for all the four equations. The null hypothesis of the DWH endogeneity test is that an ordinary least squares (OLS) estimator of the same equation would yield consistent estimates: that is, an endogeneity among the regressors would not have deleterious effects on OLS estimates. A rejection of the null hypothesis indicates that endogenous regressors' effects on the estimates are meaningful, and instrumental variables techniques are required. In fact, the rejection of the null hypothesis suggests that the ordinary least squares estimates might be biased and inconsistent and hence the OLS is not an appropriate estimation technique. Second, we may test the overidentifying restrictions in order to provide some evidence of the instruments' validity, which is tested using the Hansen test by which the null hypothesis of overidentifying restrictions cannot be rejected. In other words, the null hypothesis of instrument appropriateness cannot be rejected. In our empirical framework, we apply the GMM technique to estimate the four way interactions between renewable energy consumption, CO_2 emissions, trade and economic growth by using annual data from a sample of 24 high-and middle-income countries, over the period 1990–2011.

The GMM estimation with panel data proves advantageous to the OLS approach in a number of ways. First, the pooled cross-section and time series data allow us to estimate the relationship between economic growth, renewable energy consumption, trade, and CO_2 emissions over a long period of time for several countries. Second, any country-specific effect can be controlled by using an appropriate GMM procedure. And last, our panel estimation procedure can control for potential endogeneity that may emerge from the explanatory variables.

2.3 Data and descriptive statistics

As with [62,64], the variables used in this study are chosen in accordance with the economic theory and data availability. The sample used is annual data covering the period 1990–2011 for 24 countries categorized into two country blocks, high-and middle-income countries. The annual data for per capita GDP (constant 2005 US$), Gross Fixed Capital Formation as a proxy of capital stock (as a share of GDP) trade openness (total exports and imports as a share of GDP), CO_2 emissions (metric tons per capita), combustible renewable energy and waste (metric tons of oil equivalent) as a proxy for renewable energy consumption, domestic credit to private sector as share of GDP as a proxy for financial development, total trade as share of GDP is the proxy of trade openness, urban population as share of total population is the proxy for urbanization, foreign direct investment net inflows as share of GDP is the proxy of foreign direct investment and population in millions, oil price (measured using the spot price on West Texas Intermediate (WTI) crude oil) and oil consumption(in million tons). Data on CO_2 emissions, oil prices, and oil consumption are sourced from the British Petroleum Statistical Review of World Energy (BP, 2012). Real GDP and trade openness are taken from the Word Bank's World Development Indicators (WDI, 2012).

The specific countries selected for the study and the timeframe are dictated by the data availability. These include: (1) 12 high-income countries (Australia, Canada, France, Germany, Japan, Netherlands, Portugal, Spain, Sweden, Switzerland, United Kingdom and United States); (2) 12 middle-income countries (Algeria, Argentina, Brazil, Bulgaria, Chile, China, Colombia, Malaysia, Mexico, Thailand, Turkey, and Venezuela).[1]

The descriptive statistics of the different variables for individuals and also for the global panel are given below in Table 1. For the high-income countries, on average, the highest level of per capita GDP (50,051.15) is found for Switzerland. On the other hand, the highest average of renewable energy consumption (73,616.99) and CO_2 emissions (19.494) are recorded in the United States. In addition, the highest mean of trade openness is found for Netherlands (124.869). It is also worth highlighting that, the lowest mean of per capita GDP (16,893.33) is obtained for Portugal, and the lowest average of trade openness (22.850) and CO_2 emissions (2.238) is recorded in Japan. The lowest average of renewable energy consumption (1855.703) is obtained for Switzerland. Thereafter, the United Kingdom is the most volatile compared to the other countries in terms of economic output. It has the highest coefficient of variation (0.147) as measured by the standard deviation-to-mean ratio. In terms of CO_2 emissions, Australia is the most volatile because it has the highest coefficient of variation (0.188) compared with the other countries. The same pattern is found for renewable energy consumption (0.746) and trade openness (0.258) for Italy and Japan, respectively.

For the middle-income countries, on average, the highest average of per capita GDP is obtained for Mexico (7209.649). Moreover, the highest average of trade openness (185.669) is recorded in Malaysia. The greatest average of renewable energy consumption is obtained for Brazil (56,288.16), while, the highest average of CO_2 emissions (6.402) is for Bulgaria. The lowest average of per capita GDP is found for China (1406.43), and the lowest average of trade openness (21.660) is for Brazil. Colombia has also the lowest level of CO_2 emissions (1.558). Similarly, the lowest average of renewable energy consumption is found for Algeria (69.236). Thereafter, China is the most volatile compared to the other countries in terms of economic output. It actually

[1] It should be mentioned that the above classification was consistent with the World Bank definition for classification based on GNI in 2000, countries are classified as low income if GNI is lower than \$826, as middle income countries if \$826=GNI=\$10,065, and as high income countries if GNI is greater than \$10,065.

Table 1 Summary statistics (before taking logarithm), 1990–2011

	Descriptive statistics	Per capita GDP	ENC (kg of oil equivalent per capita)	Trade (% of GDP)	Capital (% of GDP)	FD (in %)	POP (in million)
High-income countries							
Australia	Means	30,575.08	5438.097	38.741	25.581	90.969	19.445
	Std.dev	4271.944	266.0181	3.388	1.826	23.588	1.614
	CV	0.139	0.048	0.087	0.072	0.259	0.083
Canada	Means	31,526.94	7876.312	69.078	20.200	124.768	31.024
	Std.dev	3758.881	333.703	10.001	1.575	35.229	1.991
	CV	0.119	0.042	0.144	0.077	0.282	0.064
France	Means	31,573.53	4082.057	50.034	18.952	94.300	61.521
	Std.dev	2559.317	146.486	5.201	1.257	10.799	2.285
	CV	0.081	0.035	0.103	0.066	0.114	0.037
Germany	Means	32,391.73	4118.839	65.726	20.069	107.332	81.783
	Std.dev	2741.792	136.044	16.648	2.213	9.549	0.817
	CV	0.008	0.033	0.253	0.110	0.088	0.010
Japan	Means	34,383.42	3917.473	23.002	24.886	194.930	126.608
	Std.dev	1603.456	172.666	6.018	3.400	15.901	1.307
	CV	0.046	0.044	0.261	0.136	0.081	0.010
Netherlands	Means	36,197.24	4672.18	124.869	20.559	137.186	15.907
	Std.dev	4441.95	151.561	14.461	1.573	43.974	0.533
	CV	0.122	0.032	0.105	0.076	0.320	0.033
Portugal	Means	16,893.33	2178.929	65.093	23.742	115.354	10.291
	Std.dev	1790.8	273.445	5.352	2.574	50.092	0.260
	CV	0.106	0.125	0.082	0.108	0.434	0.025

Table 1 continued

	Descriptive statistics	Per capita GDP	ENC (kg of oil equivalent per capita)	Trade (% of GDP)	Capital (% of GDP)	FD (in %)	POP (in million)
Spain	Means	23,202.78	2820.162	51.285	24.821	121.057	41.660
	Std.dev	2976.657	325.807	9.033	3.233	52.424	2.684
	CV	0.128	0.115	0.176	0.133	0.433	0.064
Sweden	Means	36,373.84	5553.251	79.635	17.867	108.581	8.946
	Std.dev	5281.386	229.731	13.480	1.816	20.547	0.237
	CV	0.145	0.041	0.169	0.101	0.189	0.026
Switzerland	Means	50,051.15	35 09.724	80.237	22.665	158.699	7.263
	Std.dev	3251.593	100.603	10.954	2.290	5.923	0.331
	CV	0.064	0.002	0.136	0.101	0.037	0.045
United Kingdom	Means	33,304.39	3621.408	55.995	16.688	143.144	59.377
	Std.dev	4913.046	222.262	4.696	1.255	36.371	1.654
	CV	0.147	0.061	0.083	0.075	0.254	0.027
United States	Means	38,214.26	7686.201	24.811	17.829	167.558	282.271
	Std.dev	4258.858	265.497	3.264	1.641	31.590	19.135
	CV	0.111	0.034	0.131	0.092	0.188	0.067
Global panel	Means	32,878.49	4621.518	60.696	21.182	130.449	62.163
	Std.dev	8488.555	1702.431	28.122	3.691	43.315	74.997
	CV	0.258	0.368	0.463	0.174	0.332	1.206

Table 1 continued

	FDI (in %)	URB (in %)	CO_2	REC	OP	OC
High-income countries						
Australia	3.239	87.263	17.502	4869.855	40.156	38.324
	6.707	1.232	0.621	600.980	27.091	4.116
	2.070	0.014	0.035	0.123	0.674	0.107
Canada	2.708	79.020	16.538	10,798.03	40.156	90.685
	2.344	1.375	0.633	1455.273	27.091	9.633
	0.865	0.017	0.038	0.134	0.674	0.106
France	2.217	78.654	6.341	12,049.1	40.156	91.607
	1.042	4.018	0.393	1357.377	27.091	3.423
	0.470	0.051	0.062	0.112	0.674	0.037
Germany	1.352	73.331	10.275	12,111.15	40.156	127.301
	2.328	0.246	0.568	8428.129	27.091	8.481
	1.722	0.003	0.055	0.695	0.674	0.006
Japan	0.137	54.623	9.409	5974.783	40.156	13.780
	0.175	4.104	0.316	827.642	27.091	1.703
	1.275	0.007	0.033	0.138	0.674	0.123
Netherlands	5.133	76.651	10.876	1992.436	40.156	66.459
	4.879	4.572	0.465	889.084	27.091	11.242
	0.950	0.059	0.042	0.446	0.674	0.169
Portugal	2.709	54.623	5.474	2784.476	40.156	13.780
	1.643	4.104	0.627	300.973	27.091	1.703
	0.606	0.007	0.114	0.108	0.674	0.123

Table 1 continued

	FDI (in %)	URB (in %)	CO_2	REC	OP	OC
Spain	3.024	76.337	6.822	4628.394	40.156	66.459
	1.559	0.612	0.841	1107.651	27.091	11.242
	0.515	0.008	0.123	0.239	0.674	0.169
Sweden	4.91	84.114	5.850	8161.86	40.156	16.498
	5.074	0.562	0.418	1694.537	27.091	0.965
	1.032	0.006	0.071	0.207	0.674	0.058
Switzerland	3.579	73.452	5.700	1855.703	40.156	12.316
	3.617	0.125	0.320	286.240	27.091	0.576
	1.010	0.001	0.056	0.154	0.674	0.046
United Kingdom	3.959	78.756	9.314	2762.021	40.156	80.016
	3.263	0.456	0.604	1715.196	27.091	3.502
	0.824	0.005	0.064	0.620	0.674	0.043
United States	1.432	79.093	19.494	73616.99	40.15677	852.066
	0.843	2.212	0.614	7805.871	27.09174	57.077
	0.589	0.027	0.031	0.106	0.674	0.066
Global panel	2.867	76.956	10.282	11796.69	40.156	139.865
	3.582	8.223	4.785	19328.46	27.091	224.670
	1.249	0.106	0.465	1.638	0.674	1.606

Table 1 continued

	Descriptive statistics	Per capita GDP	ENC (kg of oil equivalent per capita)	Trade (% of GDP)	Capital (% of GDP)	FD (in %)	POP (in million)
Middle-income countries							
Algeria	Means	2706.751	905.84	56.993	25.712	13.319	31.935
	Std.dev	298.660	101.124	8.591	3.660	12.940	3.353
	CV	0.110	0.111	0.150	0.142	0.971	0.105
Argentina	Means	8.358	7.401	3.302	2.913	2.795	3.606
	Std.dev	0.096	0.094	0.430	0.190	0.264	0.067
	CV	0.011	0.012	0.130	0.065	0.094	0.018
Brazil	Means	4582.706	1092.47	21.660	17.715	47.719	8951832
	Std.dev	527.300	118.438	4.638	1.559	24.081	4.20e+07
	CV	0.115	0.108	0.214	0.088	0.504	0.000
Bulgaria	Means	3208.169	2534.196	108.846	19.640	45.976	8.054
	Std.dev	803.448	216.166	18.262	6.025	25.483	0.403
	CV	0.250	0.085	0.167	0.306	0.5542	0.050
Chile	Means	6669.1	1531.406	63.472	22.534	65.562	15.441
	Std.dev	1398.652	269.468	7.569	2.520	13.807	1.252
	CV	0.209	0.175	0.119	0.111	0.210	0.081
China	Means	1406.43	1096.303	48.265	36.846	106.709	1256.277
	Std.dev	801.143	327.934	12.924	5.327	14.846	64.202
	CV	0.569	0.299	0.267	0.144	0.120	0.051
Colombia	Means	3295.388	683.138	35.510	19.241	32.503	39.883
	Std.dev	380.732	52.757	1.587	3.300	6.170	3.989
	CV	0.115	0.077	0.044	0.171	0.189	0.100

Table 1 continued

	Descriptive statistics	Per capita GDP	ENC (kg of oil equivalent per capita)	Trade (% of GDP)	Capital (% of GDP)	FD (in %)	POP (in million)
Malaysia	Means	4917.785	2009.739	185.669	28.814	116.332	23.554
	Std.dev	974.035	425.978	21.941	8.506	22.938	3.281
	CV	0.198064	0.211	0.118	0.295	0.197	0.139
Mexico	Means	7209.649	1452.8	53.867	19.811	22.316	103.721
	Std.dev	604.4149	66.162	10.206	1.444	5.899	10.149
	CV	0.83283	0.045	0.189	0.072	0.264	0.097
Thailand	Means	2401.977	1237.223	113.414	30.166	132.614	62.318
	Std.dev	464.713	295.135	26.661	7.676	22.275	3.499
	CV	0.193	0.238	0.235	0.254	0.167	0.056
Turkey	Means	6320.722	1190.049	44.903	21.350	23.076	63.576
	Std.dev	1052.293	176.704	7.685	3.027	9.864	5.913
	CV	0.166	0.148	0.171	0.141	0.427	0.093
Venezuela	Means	5581.466	2369.318	51.322	20.541	17.057	24.637
	Std.dev	511.952	136.772	6.166	3.686	6.194	3.014
	CV	0.091724	0.057	0.1205	0.179	0.363	0.122
Global panel	Means	4382.158	1479.017	67.794	23.425	53.348	746124.9
	Std.dev	1905.47	592.194	46.533	7.230	43.682	1.21e+07
	CV	0.434	0.400	0.686	0.308	0.818	0.001

Table 1 continued

	FDI (in %)	URB (in %)	CO_2	REC	OP	OC
Middle-income countries						
Algeria	1.055	61.934	3.037	69.236	40.156	10.378
	0.665	6.656	0.236	23.896	27.091	2.477
	0.630	0.107	0.077	0.345	0.674	0.238
Argentina	0.747	90.059	3.843	2528.223	40.156	21.396
	0.496	1.727	0.348	433.187	27.091	2.398
	0.664	0.019	0.090	0.171	0.674	0.112
Brazil	2.223	80.343	1.743	56288.16	40.156	90.566
	1.477	3.355	0.183	11520.73	27.091	15.719
	0.664	0.041	0.105	0.204	0.674	0.173
Bulgaria	7.552	69.276	6.402	489.007	40.156	4.485
	8.475	1.939	0.787	268.734	27.091	0.607
	1.122	0.027	0.122	0.549	0.674	0.135
Chile	5.723	86.1586	3.403	4457.493	40.156	11.638
	2.475	1.920	0.559	651.694	27.0917	3.445
	0.429	0.022	0.164	0.146	0.674	0.295
China	3.789	36.342	3.348	203574.9	40.156	254.439
	1.296	7.350	1.092	1149.176	27.091	107.351
	0.342	0.202	0.326	0.005	0.674	0.421
Colombia	2.828	72.092	1.558	4170.281	40.156	11.056
	1.495	2.112	0.167	935.361	27.091	1.018
	0.528	0.029	0.107	0.224	0.674	0.092

Table 1 continued

	FDI (in %)	URB (in %)	CO_2	REC	OP	OC
Malaysia	4.337	62.012	5.631	2908.366	40.156	22.288
	2.108	7.289	1.193	336.758	27.091	5.217
	0.486	0.117	0.211	0.115	0.674	0.234
Mexico	2.566	74.901	3.741	8711.38	40.156	83.526
	0.920	2.020	0.159	221.295	27.091	6.627
	0.358	0.026	0.042	0.025	0.674	0.079
Thailand	3.030	31.448	3.329	15974.45	40.156	36.872
	1.443	1.406	0.751	2556.81	27.091	8.508
	0.475	0.044	0.225	0.160	0.6746	0.230
Turkey	1.130	64.954	3.258	6143.015	40.156	29.192
	1.056	3.548	0.4201	1005.633	27.091	3.246
	0.934	0.054	0.128	0.163	0.674	0.111
Venezuela	1.998	89.631	6.374	873.464	40.156	26.309
	1.873	2.903	0.627	60.886	27.091	5.831
	0.937	0.032	0.098	0.069	0.674	0.221
Global panel	3.222	68.263	3.806	25515.67	40.156	50.179
	3.343	18.558	1.641	55901.16	26.519	73.9561
	1.037	0.271	0.431	2.190	0.674	1.473

Std standard deviation, *ENC* per capita energy consumption, *FD* financial development, *POP* population, *FDI* foreign direct investment, *URB* urbanisation, *REC* renewable energy consumption, *OP* oil price, *OC* oil consumption has the highest coefficient of variation (0.569). In terms of CO_2 emissions, China is the most volatile compared to the overall panel because it has the greatest coefficient of variation (0.326). The same pattern is found for renewable energy consumption (0.549) and trade openness (0.267) for Bulgaria and China, respectively.

According to the statistics recorded in both high-and middle- income countries, it is clear that the greatest average of the per capita GDP is recorded for the high-income countries compared to the middle-income ones. It is also worth highlighting that high-income countries' overall economic wealth is almost seven times as much as that of middle-income countries. The coefficient of variation, suggests that the middle-income countries is the most volatile compared to the high-income ones in terms of economic output, it is the greatest coefficient of variation (0.434). Moreover, the results postulate that, high-income countries have the greatest coefficient of variation (0.475), which explains, in fact that the high-income countries have more pollutants activities. Moreover, in terms of renewable energy consumption, the middle-income countries have the highest coefficient (2.190). In addition, the average of FD is the highest for high-income countries compared to the middle-income ones.

3 Results

3.1 Results of panel unit root tests

The LLC and IPS unit root tests are used in this paper to test for stationarity of the panel data obtained for two country blocks.

Table 2 shows the results of the panel unit root tests for levels and also for the first difference of variables. It can be seen from the Table 2, that in the overall all the variables are statistically significant under the LLC and IPS tests, in the second difference form. This implies that the variables are integrated at I (2).

While estimating the four-way linkages between trade openness, renewable energy consumption, CO_2 emissions, and economic growth, K, POP, OP, OC, URB, FD and FDI are included as instrumental variables.

In addition, before running the regressions, two specific tests have been audited. According to [50,74], two important specification tests are used for simultaneous-equation regression models: First, we may test the overidentifying restrictions in order to provide some evidence of the instrument' validity, which is tested using the Hansen test by which the null hypothesis of overidentifying restrictions cannot be rejected. This means that, the null hypothesis that the instruments are appropriate cannot be rejected. First, the Durbin-Wu-Hausman (DWH) test was used to test the endogeneity for the four equations. The null hypothesis of the DWH endogeneity test is that an ordinary least squares (OLS) estimator of the same equation would yield consistent estimates, that is, an endogeneity among the regressors would not have deleterious effects on the OLS estimates. A rejection of the null hypothesis indicates that endogenous regressors' effects on the estimates are meaningful, and instrumental variables techniques are required.

Based on the above diagnostic tests, the estimated coefficients of Eqs. (5), (6), (7), (8) are given in Tables 3, 4, 5, 6, 7, 8, 9 and 10.

Table 2 Results of panel unit root tests

Variables	LLC test						IPS test					
	Level		First difference		Second difference		Level		First difference		Second difference	
	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value
High-income countries												
GDP	0.053 (0)*	0.0001	35.234 (1)	1.0000	−18.156 (0)*	0.0000	1.966 (1)	0.975	7.431 (1)	1.000	−27.611 (0)*	0.000
REC	−2.727 (0)*	0.0032	16.451 (1)	1.0000	−17.474 (0)*	0.0000	−0.487 (1)	0.313	4.743 (1)	1.000	−24.499 (0)*	0.000
T	−1.638 (0)*	0.0507	14.963 (1)	1.0000	−17.555 (0)*	0.0000	1.263 (1)	0.897	3.315 (1)	1.000	−24.450 (0)*	0.000
K	0.170 (2)	0.5679	5.636 (1)	1.0000	−15.959 (0)*	0.0000	2.484 (1)	0.993	0.332 (1)	0.630	−21.776 (0)*	0.000
FD	−2.580 (0)*	0.0049	0.253 (1)	0.5999	−21.722 (0)*	0.0000	−0.334 (1)	0.369	−3.524 (0)*	0.0000	−26.770 (0)*	0.000
POP	−0.120 (2)	0.4522	69.954 (1)	1.0000	−20.586 (0)*	0.0000	5.198 (1)	1.000	9.663 (1)	1.000	−29.493 (0)*	0.000
FDI	−9.007 (0)*	0.0000	−21.813 (0)*	0.0000	−33.503 (0)*	0.0000	−7.836 (0)*	0.0000	−21.701 (0)*	0.0000	−33.509 (0)*	0.000
URB	−0.474 (2)	0.3175	212.748 (1)	1.0000	−20.562 (0)*	0.0000	3.939 (1)	1.0000	11.566 (1)	1.000	−29.675 (0)*	0.000
CO_2	−10.750 (0)*	0.0000	−9.134 (0)*	0.0000	−20.050 (0)*	0.0000	−7.079 (0)*	0.0000	−5.451 (0)*	0.0000	−28.237 (0)*	0.000
OP	−3.713 (0)*	0.0001	−10.001 (0)*	0.0000	−20.808 (0)*	0.0000	−3.478 (0)*	0.0003	−9.665 (0)*	0.0000	−30.299 (0)*	0.000
OC	−1.249 (2)	0.1058	23.824 (1)	1.0000	−22.167 (0)*	0.0000	0.225 (1)	0.589	3.529 (1)	1.000	−29.855 (0)*	0.000
Middle-income countries												
GDP	−3.183 (0)*	0.0007	51.803 (1)	1.0000	−20.410 (0)*	0.0000	−0.796 (0)*	0.213	5.187 (1)	1.000	−29.257 (0)*	0.0000
REC	−0.359 (2)	0.3596	15.493 (1)	1.0000	−19.572 (0)*	0.0000	1.594 (1)	0.945	2.663 (1)	0.996	−27.115 (0)*	0.000
T	−2.637 (0)*	0.0042	4.119 (1)	1.0000	−18.150 (0)*	0.0000	−0.438 (1)	0.331	0.165 (1)	0.565	−23.527 (0)*	0.0000
K	−2.867 (0)*	0.0021	−1.722 (0)*	0.0425	−18.286 (0)*	0.0000	−1.233 (1)	0.109	−3.484 (0)*	0.0000	−22.232 (0)*	0.0000
FD	−1.119 (1)	0.1314	2.149 (1)	0.9842	−18.610 (0)*	0.0000	1.261 (1)	0.896	−1.544 (0)*	0.061	−24.452 (0)*	0.0000
POP	−11.660 (0)*	0.0000	5.846 (1)	1.0000	−22.153 (0)*	0.0000	−10.062 (0)*	0.0000	−1.994 (0)*	0.023	−28.510 (0)*	0.0000
FDI	−6.482 (0)*	0.0000	−12.164 (0)*	0.0000	−21.860 (0)*	0.0000	−5.703 (0)*	0.0000	−12.471 (0)*	0.0000	−25.048 (0)*	0.0000

Table 2 continued

Variables	LLC test						IPS test					
	Level		First difference		Second difference		Level		First difference		Second difference	
	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value	T-Statistics	Prob. value
URB	4.632 (2)	1.0000	776.558 (1)	1.0000	−20.471 (0)*	0.0000	8.643 (2)	1.000	10.603 (1)	1.000	−29.470 (0)*	0.000
CO2	−1.714 (0)*	0.0432	1.329 (1)	0.9081	−20.960 (0)*	0.0000	0.751 (1)	0.774	−2.208 (0)*	0.014	−25.933 (0)*	0.000
OP	−3.713 (0)*	0.0001	−17.297 (0)*	0.0000	−20.808 (0)*	0.0000	−3.478 (0)*	0.0003	−9.665 (0)*	0.0000	−30.299 (0)*	0.000
OC	−1.858 (0)*	0.0316	19.7102 (1)	1.0000	−19.257 (0)*	0.0000	0.156 (2)	0.562	4.486 (1)	1.000	−26.929 (0)*	0.000

All panel unit root tests were performed with restricted intercept and trend for all variables. In addition, Lag length of variables is shown in small parentheses.*, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 3 Simultaneous equations GMM-estimation for Eq. 5

Independent variables	Dependent variable: economic growth				
	Constant	RE	C	T	K
Australia	9.379 (0.191)	−0.420 (0.812)	−3.852 (0.218)	2.594 (0.371)	1.869 (0.130)
Canada	1.412 (0.112)	0.818 (0.000)*	0.536 (0.214)	−0.193 (0.06)***	0.221 (0.150)
France	9.356 (0.001)*	0.109 (0.224)	−0.900 (0.235)	0.365 (0.330)	0.070 (0.740)
Germany	9.509 (0.000)*	0.03 (0.068)***	−0.246 (0.108)	0.212 (0.000)*	0.089 (0.096)***
Japan	9.767 (0.000)*	−0.003 (0.966)	0.194 (0.000)*	0.146 (0.000)*	−0.057 (0.048)
Netherlands	9.937 (0.000)*	0.288 (0.001)*	−0.671 (0.041)**	−0.129 (0.588)	0.205 (0.099)***
Portugal	5.590 (0.000)*	0.173 (0.423)	0.614 (0.000)*	0.480 (0.007)*	−0.090 (0.501)
Spain	5.612 (0.000)*	0.208 (0.000)*	−0.180 (0.699)	0.468 (0.029)**	0.369 (0.115)
Sweden	5.044 (0.000)*	0.448 (0.000)*	−0.279 (0.380)	0.204 (0.214)	0.352 (0.000)*
Switzerland	5.660 (0.000)*	0.530 (0.000)*	−0.002 (0.979)	0.045 (0.396)	0.314 (0.000)*
United Kingdom	6.272 (0.000)*	0.300 (0.000)*	0.287 (0.141)	−0.210 (0.591)	0.715 (0.000)*
United States	−19.690 (0.125)	2.507 (0.030)**	0.346 (0.540)	−0.738 (0.322)	1.204 (0.006)*
Panel	11.082 (0.000)*	−0.138 (0.027)**	0.748 (0.000)*	0.158 (0.086)***	−0.601 (0.000)*
Hansen test (p-value)	0.461 (0.7354)				
DWH test (p-value)	37.895 (0.0000)				

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 4 Simultaneous equations GMM-estimation for Eq. 6

Independent variables	Dependent variable: renewable energy consumption					
	Constant	gdp	c	t	op	oc
Australia	0.433 (0.875)	0.341 (0.416)	0.634 (0.404)	0.419 (0.576)	−0.035 (0.676)	0.357 (0.587)
Canada	3.692 (0.365)	0.458 (0.438)	−1.817 (0.015)**	0.342 (0.167)	−0.037 (0.678)	1.026(0.071)***
France	−22.817 (0.833)	3.806 (0.709)	1.755 (0.865)	−2.529 (0.145)	0.099 (0.825)	−0.204(0.913)
Germany	−34.216 (0.322)	6.787 (0.033)**	−1.579 (0.440)	−1.689 (0.050)***	0.325 (0.134)	−3.610(0.012)**
Japan	−6.290 (0.888)	1.440 (0.754)	0.193 (0.921)	0.647 (0.422)	−0.186 (0.207)	−0.338 (0.605)
Netherlands	−35.788 (0.000)*	6.027 (0.000)*	0.054 (0.979)	−2.934(0.080)***	0.381 (0.001)*	−1.935 (0.121)
Portugal	2.237 (0.438)	0.651 (0.134)	0.155 (0.712)	−0.107 (0.658)	0.081 (0.000)*	−0.287 (0.196)
Spain	−17.626 (0.006)*	3.140 (0.000)*	−1.295 (0.000)*	0.168 (0.491)	0.089 (0.231)	−0.954 (0.027)
Sweden	15.179 (0.023)**	−1.294 (0.060)**	1.372 (0.019)**	1.664 (0.000)*	0.196 (0.023)**	−1.070 (0.174)
Switzerland	26.619 (0.574)	−1.996 (0.692)	−2.222 (0.102)	0.574 (0.718)	0.247 (0.378)	1.188 (0.352)
United Kingdom	−19.248 (0.122)	0.609 (0.595)	−3.292 (0.036)**	6.129 (0.004)*	0.033 (0.798)	0.731 (0.41)
United States	5.235 (0.027)**	1.760 (0.000)*	0.594 (0.189)	−0.175 (0.551)	0.035 (0.459)	−2.064 (0.000)*
Panel	6.572 (0.012)**	−0.779 (0.002)*	0.699 (0.005)*	1.044 (0.000)*	0.288 (0.007)*	0.819 (0.000)*
Hansen test (p-value)	4.018 (0.1152)					
DWH test (p-value)	49.877 (0.0000)					

Notes: Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1%, 5%, and 10% levels, respectively

Table 5 Simultaneous equations GMM-estimation for Eq. 7

Independent variables	Dependent variable: CO_2 emissions					
	Constant	GDP	RE	T	URB	FD
Australia	13.777 (0.113)	−1.894 (0.218)	0.512 (0.113)	−0.160 (0.518)	0.170 (0.965)	0.917 (0.104)
Canada	37.686 (0.205)	0.495 (0.142)	1.060 (0.329)	−0.055 (0.750)	−11.437 (0.227)	0.075 (0.119)
France	10.549 (0.022)**	−1.009 (0.287)	0.133 (0.689)	0.486 (0.503)	−0.439 (0.636)	0.112 (0.668)
Germany	−90.100 (0.045)**	−0.054 (0.952)	−0.258 (0.015)**	0.241 (0.323)	21.987(0.043)**	−0.012 (0.942)
Japan	−23.479 (0.000)*	3.060 (0.000)*	−0.006 (0.985)	−0.315 (0.002)*	−0.989(0.001)*	−0.161 (0.230)
Netherlands	5.225 (0.037)**	−0.980 (0.100)	−0.019 (0.946)	0.068 (0.884)	1.695 (0.251)	−0.019 (0.934)
Portugal	−13.001(0.080)***	2.198 (0.000)*	−0.287 (0.426)	−0.726 (0.001)*	−0.208 (0.778)	−0.118 (0.597)
Spain	24.990 (0.035)	1.808 (0.000)*	0.151 (0.486)	−0.057 (0.847)	−9.527 (0.274)	−0.210 (0.217)
Sweden	121.337 (0.393)	−0.533 (0.123)	1.303 (0.281)	−0.311 (0.556)	−28.069 (0.413)	0.017 (0.859)
Switzerland	20.853 (0.797)	0.943 (0.176)	−0.409 (0.519)	−0.218 (0.800)	−6.300 (0.759)	0.352 (0.388)
United Kingdom	−50.447 (0.138)	−0.222 (0.399)	−0.104 (0.258)	0.429 (0.451)	12.596 (0.120)	−0.187 (0.135)
United States	8.022 (0.016)**	−0.377 (0.582)	−0.786 (0.016)**	0.511 (0.007)*	1.423 (0.485)	−0.022 (0.916)
Panel	−0.297 (0.073)***	1.020 (0.019)**	0.196 (0.000)*	−0.145 (0.337)	2.381 (0.035)**	0.341 (0.271)
Hansen test (p-value)	1.026 (0.1102)					
DWH test (p-value)	51.966 0.0000					

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 6 Simultaneous equations GMM-estimation for Eq. 8

Independent variables	Dependent variable: trade				
	Constant	GDP	RE	C	FDI
Australia	1.526 (0.558)	−0.356 (0.263)	1.224 (0.000)*	−1.606 (0.178)	0.022 (0.110)
Canada	3.299 (0.240)	−2.448 (0.000)*	2.109 (0.000)*	2.370 (0.015)**	0.064 (0.072)***
France	−17.301 (0.017)**	2.085 (0.000)*	−0.298 (0.009)*	1.313 (0.176)	−0.011 (0.614)
Germany	−31.628 (0.005)*	3.489 (0.002)*	−0.031 (0.809)	−0.079 (0.902)	0.000 (0.971)
Japan	−82.750 (0.005)*	9.707 (0.020)**	−1.371 (0.354)	−1.594 (0.059)***	0.018 (0.201)
Netherlands	3.707 (0.368)	0.096 (0.861)	0.163 (0.404)	−0.477 (0.510)	0.003 (0.868)
Portugal	−12.464 (0.010)**	2.670 (0.012)**	−0.866 (0.140)	−1.450 (0.018)**	−0.021 (0.531)
Spain	−21.360 (0.003)*	3.611 (0.002)*	−1.015 (0.004)*	−1.282 (0.127)	−0.005 (0.911)
Sweden	−7.687 (0.007)*	0.565 (0.105)	0.544 (0.024)**	0.655 (0.168)	0.054 (0.000)*
Switzerland	−13.295 (0.000)*	1.242 (0.048)**	0.474 (0.196)	0.376 (0.475)	0.012 (0.175)
United Kingdom	6.757 (0.122)	−0.490 (0.235)	0.227 (0.001)*	0.266 (0.416)	0.019 (0.242)
United States	−11.205 (0.000)*	0.351 (0.000)*	0.830 (0.000)*	0.471 (0.248)	0.036 (0.026)**
Panel	0.307 (0.013)**	0.526 (0.000)*	0.055 (0.272)	−1.048 (0.000)*	0.159* (0.000)
Hansen test (p-value)	2.748 (0.1342)				
DWH test (p-value)	93.481 (0.0000)				

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 7 Simultaneous equations GMM-estimation for Eq. 5

Independent variables	Dependent variable: economic growth				
	Constant	RE	C	T	K
Algeria	3.769 (0.000)*	0.002 (0.931)***	−0.696 (0.071)***	0.685 (0.000)*	0.653 (0.000)*
Argentina	3.339 (0.000)*	0.484 (0.000)*	0.782 (0.088)***	−0.170 (0.003)*	0.254 (0.047)**
Brazil	2.778 (0.029)**	0.455 (0.000)*	0.476 (0.002)*	−0.088 (0.370)	0.232 (0.063)*
Bulgaria	4.111 (0.000)*	0.109 (0.071)***	0.366 (0.021)**	0.254 (0.210)	0.470 (0.000)*
Chile	−7.403 (0.001)*	1.756 (0.000)*	−0.303 (0.225)	0.160 (0.423)	0.370 (0.001)*
China	232.147 (0.080)***	−19.364 (0.079)***	0.322 (0.512)	0.888 (0.081)***	2.186 (0.017)**
Colombia	3.512 (0.425)	−0.225 (0.208)	−0.071 (0.864)	1.650 (0.138)	0.198 (0.159)
Malaysia	46.450 (0.262)	−4.305 (0.350)	2.411 (0.173)	−0.862 (0.347)	−0.098 (0.280)
Mexico	16.410 (0.001)*	−1.155 (0.029)**	1.355* (0.000)	0.142 (0.001)*	0.199 (0.291)
Thailand	−4.884 (0.773)	2.366 (0.558)	1.266 (0.342)	−1.960 (0.615)	−0.738 (0.652)
Turkey	13.524 (0.000)*	−0.775 (0.000)*	−0.000 (0.997)	0.329 (0.054)*	0.234 (0.001)*
Venezuela	4.397 (0.142)	1.713 (0.133)	−2.182 (0.141)	−0.856 (0.392)	0.012 (0.964)
Panel	7.945 (0.000)*	0.109 (0.026)**	3.898 (0.000)*	−0.720 (0.007)*	0.817 (0.034)**
Hansen test (p-value)	0.613 (0.7359)				
DWH test (p-value)	164.216 (0.0000)				

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 8 Simultaneous equations GMM-estimation for Eq.6

Independent variables	Dependent variable: renewable energy consumption					
	Constant	GDP	C	T	OP	OC
Algeria	−268.311 (0.232)	21.830 (0.339)	41.522 (0.241)	18.923 (0.144)	−0.135 (0.257)	−7.526 (0.435)
Argentina	−3.095 (0.461)	2.108 (0.011)**	−2.795 (0.005)*	0.235 (0.416)	0.005 (0.394)	−1.291 (0.161)
Brazil	−8.835 (0.223)	2.832 (0.008)*	0.448 (0.239)	0.256 (0.019)**	−0.001 (0.615)	−1.129(0.036)**
Bulgaria	−12.969 (0.212)	2.029 (0.025)**	−3.641 (0.001)*	1.40 (0.069)***	−0.006 (0.488)	2.082 (0.006)*
Chile	−0.646 (0.721)	0.506 (0.069)***	−0.208 (0.337)	0.994 (0.127)	−0.005 (0.111)	0.397 (0.309)
China	12.080 (0.000)*	0.094 (0.001)*	−0.013 (0.243)	0.066 (0.000)	−0.000* (0.009)	−0.139 (0.001)*
Colombia	12.057 (0.354)	0.162 (0.941)	2.205 (0.013)**	−1.275 (0.748)	−0.000 (0.977)	−0.613 (0.520)
Malaysia	12.085 (0.019)**	−0.656 (0.411)	−0.388 (0.299)	−0.442 (0.064)*	−0.001 (0.537)	1.449 (0.019)**
Mexico	9.797 (0.004)*	−0.121 (0.850)	0.849 (0.032)**	0.083 (0.137)	0.000***(0.091)	−0.240 (0.639)
Thailand	−6.927 (0.581)	2.706 (0.163)	−0.052 (0.914)	0.523 (0.325)	−0.002 (0.639)	−1.873 (0.119)
Turkey	−9.506 (0.934)	3.578 (0.850)	3.602 (0.759)	−1.295 (0.889)	−0.024 (0.783)	−3.385 (0.718)
Venezuela	−4.824 (0.655)	0.738 (0.396)	2.077 (0.276)	0.634 (0.230)	0.001 (0.646)	−0.363 (0.581)
Panel	−27.478 (0.000)*	2.925 (0.000)*	−8.380 (0.004)*	4.190 (0.000)*	−0.019 (0.010)**	1.824 (0.000)*
Hansen test (p-value)	1.495 (0.2215)					
DWH test (p-value)	146.561 (0.0000)					

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 9 Simultaneous equations GMM-estimation for Eq 7

Independent variables	Dependent variable: CO_2 emissions					
	Constant	GDP	RE	T	URB	FD
Algeria	−2.081 (0.656)	0.123 (0.930)	−0.172 (0.308)	−0.219 (0.442)	0.956 (0.534)	−0.053 (0.208)
Argentina	30.245 (0.239)	0.385 (0.293)	−0.538 (0.129)	0.602 (0.143)	−6.819 (0.204)	0.282 (0.426)
Brazil	−7.521 (0.268)	0.195 (0.876)	−0.475 (0.424)	0.113 (0.771)	2.625 (0.289)	−0.065 (0.221)
Bulgaria	−34.958 (0.216)	2.233 (0.002)*	−1.107 (0.026)**	0.502 (0.309)	5.783 (0.359)	−0.365 (0.047)**
Chile	39.369 (0.000)*	0.949 (0.001)*	0.842 (0.080)***	0.282 (0.263)	−12.591 (0.000)*	0.328 (0.047)**
China	−449.946 (0.218)	−9.777 (0.181)	34.828 (0.222)	−0.207 (0.789)	30.916 (0.171)	−3.211 (0.092)*
Colombia	3.106 (0.852)	−0.281 (0.783)	0.196 (0.502)	0.343 (0.789)	−1.017 (0.815)	0.317 (0.074)***
Malaysia	−24.228 (0.000)*	1.115 (0.000)*	4.036* (0.006)	0.111 (0.542)	−4.237 (0.003)*	0.248 (0.019)**
Mexico	14.398 (0.465)	1.221 (0.035)**	−1.057 (0.453)	0.095 (0.555)	−3.424 (0.251)	0.023 (0.546)
Thailand	11.271 (0.247)	1.858 (0.000)*	−1.347 (0.161)	0.875 (0.100)*	−4.091 (0.424)	−0.311 (0.435)
Turkey	27.267 (0.461)	−0.142 (0.921)	−1.286 (0.416)	1.032 (0.254)	−4.184 (0.323)	−0.028 (0.824)
Venezuela	5.826 (0.421)	−0.998 (0.174)	1.678 (0.345)	−0.431 (0.003)*	−1.203 (0.727)	0.137 (0.404)
Panel	−1.522 (0.066)***	0.291 (0.045)**	−0.022 (0.496)	0.278 (0.037)**	−0.112 (0.806)	−0.028 (0.677)
Hansen test (p-value)	3.209 (0.0732)					
DWH test (p-value)	48.799 (0.0000)					

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

Table 10 Simultaneous equations GMM-estimation for Eq. 8

Independent variables	Dependent variable: trade				
	Constant	GDP	RE	C	FDI
Algeria	−2.000 (0.608)	1.174 (0.021)**	−0.219 (0.400)	−2.043 (0.090)*	0.071 (0.255)
Argentina	4.499 (0.580)	−3.404 (0.020)**	2.370 (0.000)*	6.631 (0.000)*	−0.245 (0.084)***
Brazil	2.080 (0.878)	−4.960 (0.242)	4.090 (0.109)	−3.973 (0.445)	0.576 (0.316)
Bulgaria	4.307 (0.000)*	−0.015 (0.945)	−0.010 (0.931)	0.232 (0.519)	0.098 (0.000)*
Chile	−4.061 (0.220)	0.165 (0.751)	0.854 (0.374)	−0.232 (0.557)	−0.088 (0.261)
China	542.248 (0.004)*	0.098 (0.326)	−44.196 (0.004)*	0.375 (0.068)*	0.557 (0.001)*
Colombia	0.776 (0.682)	0.165 (0.084)*	0.179 (0.387)	−0.165 (0.629)	0.041 (0.222)
Malaysia	3.478 (0.108)	−0.805 (0.139)	0.889 (0.189)	0.825 (0.008)***	0.051 (0.075)*
Mexico	−42.288 (0.190)	3.817 (0.005)***	2.227 (0.406)	−6.062 (0.013)**	0.155 (0.121)
Thailand	−3.771 (0.172)	0.092 (0.903)	0.730 (0.045)**	0.456 (0.303)	0.138 (0.006)*
Turkey	−16.543 (0.180)	1.476 (0.097)*	0.751 (0.231)	0.731 (0.234)	−0.066 (0.236)
Venezuela	5.408 (0.112)	−0.721 (0.157)	1.218 (0.124)	−1.886 (0.004)*	−0.021 (0.350)
Panel	5.277 (0.000)*	−0.766 (0.000)*	0.089 (0.075)*	3.457 (0.000)*	0.025 (0.748)
Hansen test (p-value)	6.088 (0.1477)				
DWH test (p-value)	138.915 (0.0000)				

Values in parentheses are the estimated p-values. Hansen J-test refers to the over-identification test for the restrictions in GMM estimation. DWH-test is the Durbin–Wu–Hausman test for endogeneity. *, **, and *** indicate significance at 1, 5, and 10 % levels, respectively

3.1.1 Results for the high-income countries

The empirical results about Eq. (5) are presented in Table 3, which shows that renewable energy consumption has a positive and significant impact on the per capita GDP for Canada, Germany, Netherlands, Spain, Sweden, Switzerland, the UK, and the US. For the remaining countries, no significant relationship is found. For the panel results, RE has a negative impact on economic growth at 1 % level. The magnitude of 0.138 implies that a 1 % increase in RE decreases economic growth by around 0.138 %. This result is consistent with the findings of [81]. In addition, CO_2 emissions have a positive and significant impact on economic growth for Japan and Portugal. Besides, the per capita CO_2 emissions have a negative and significant impact on the per capita GDP for the Netherlands. For the remaining countries, no significant relationship is found. For the panel results, the per capita CO_2 emissions have a positive and significant impact on economic growth at 1 % level. The magnitude of 0.748 implies that a 1 % increase in CO_2 emissions increases economic growth by around 0.75 %. This result is consistent with the findings of [57]. On the other hand, trade openness has a positive and significant impact on economic growth only for Germany, Japan, Portugal, and Spain. Whereas, a negative relationship is found for Canada. However, for the rest of countries, no significant relationship is found. The panel estimation shows that trade openness has a positive and significant impact on economic growth at 10 % level. The magnitude of 0.158 implies that a 1 % increase in trade openness increases economic growth by around 0.16 %. This finding is in line with that of Shahbaz et al. (2013). Finally, the Coefficient of capital significantly affects the per capita GDP for Germany, the Netherlands, Sweden, Switzerland, the UK and the US. Indeed, a 1 % increase in capital increases economic growth within a range of 0.089 % (Germany) to 1.204 % (United States). On the other hand, capital has a negative impact on economic growth only for Japan. For the remaining countries, no significant relationship is found. The panel result shows that capital has a negative and significant impact on the per capita GDP at 1 % level. The magnitude of 0.601 means that a 1 % rise in the capital stock decreases economic growth by around 0.601 %.This result is in line with the findings of [63].

The empirical results pertaining to Eq. (7) are reported in Table 4, which shows that economic growth has a positive and significant effect on renewable energy consumption for Germany, Netherlands, Spain and the United States. Indeed, a 1 % increase in economic growth increases renewable energy consumption within a range of 1.76 % (the United States) to 6.787 % (Germany). While, economic growth has a negative on renewable energy consumption only for Sweden. However, for the remaining countries, no significant relationship is found. The panel result shows that the per capita GDP has a negative and significant impact on renewable energy consumption at 1 % level. The magnitude of 0.779 indicates that a 1 % increase in the per capita GDP decreases renewable energy consumption by around 0.8 %. This result is consistent with the finding of [51]. Regarding the pollutant variable, we find that CO_2 emissions have a positive and significant impact on the demand of renewable energy only for Sweden. This implies that higher CO_2 emissions in these countries create demand for cleaner environment and encourage the use of alternative energy free from this evil effect. While, CO_2 emissions have a negative and significant impact for Canada, Spain and the UK. However no significant relationship is found for the rest of the countries. The panel estimation indicates that CO_2 emissions have a positive and significant impact on renewable energy consumption at 1 % level. The magnitude of 0.699 means that a 1 % rise in pollutant emissions raises renewable energy consumption by around 0.7 %. This result is in line with the findings of [62]. In addition, trade openness has a significant impact on renewable energy consumption for 4 countries out of 12. In the case of Germany and the Netherlands, trade openness has a negative and significant impact. For Sweden and the UK, there is evidence of a positive impact of trade openness on renewable energy consumption. For the rest of countries, no significant relationship is found. Regarding the panel results, trade openness has a positive impact on renewable energy consumption at 1 % level. This result is in line with the findings of [65]. Moreover, the impact of real oil price on the demand of renewable energy is positive and significant for Netherlands, Portugal and Spain. For the remaining countries, no significant relationship is found. Regarding the panel results, oil price has a positive impact on renewable energy consumption at 10 % level. Finally, oil consumption has a significant impact on renewable energy consumption for 3 countries out of 12. It has a negative and significant impact on renewable energy consumption for Germany and the US. This indicates that a reduction in oil consumption leads to an increase in renewable energy demand. Thus, the above results imply that under the upsurge of international crude oil prices and oil supply shortages, countries can develop renewable energy to replace their demands for oil. Whereas, it has a positive impact only for Canada indicating that a 1 % increase in oil consumption increases the demand of renewable energy by around 1.026 %. However, no significant relationship is found for the rest of the countries. The panel estimation indicates that oil consumption has a positive and significant impact on renewable energy consumption at 1 % level. The magnitude of 0.819 means that a 1 % rise in oil consumption raises renewable energy consumption by around 0.82 %.

Table 5 presents the estimated results about Eq. (7). It appears that the per capita GDP has a positive and statistically significant impact on CO_2 emissions for Japan, Portugal and Spain. However, for the remaining countries, no significant relationship is found. The panel result shows that the per capita GDP has a positive and significant impact on CO_2 emissions at 5 % level. The magnitude of 0.469 indicates that a 1 % increase in the per capita GDP increases CO_2 emissions by around 0.47 %. These results are consistent with the findings of [16,27,30,35,41,61,78]. Regarding the renewable energy consumption variable, it is found that renewable energy consumption has a negative and significant impact on CO_2 emissions only for Germany and the US. For the remaining countries, no significant relationship is found. On the other hand, the panel results show that renewable energy consumption has a significant positive impact on CO_2 emissions at 1 % level. The magnitude of 0.196 indicates that a 1 % increase in renewable energy consumption increases CO_2 emissions by around 0.196 %. These results are consistent with the findings of [15]. Nevertheless, trade openness has a positive and significant impact on CO_2 emissions only for the US. This result is in line with Andersson et al. (2009). Moreover, trade has a negative impact on CO_2 emissions only for Portugal than in Japan. However, no significant relationship is found for the rest of the countries. The panel estimation shows that openness has a negative insignificant impact. Thereafter, the coefficient of urbanization has a positive and significant impact on CO_2 emissions only for Germany. It has a negative significant impact only for Japan. On the other hand, no significant relationship is found for the rest of the countries. Regarding the panel estimation, urbanization has a significant positive impact on CO_2 emissions at 5 % level. The magnitude of 2.381 indicates that a 1 % increase in urbanization increases CO_2 emissions by around 2.381 %. These results are in line with the findings of [32]. Finally, The Coefficient of financial development impact on CO_2 emissions is insignificant positive for all the countries. Moreover, for the global panel results, financial development has insignificant positive impact on CO_2 emissions, indicating that financial development has not taken place at the expense of the CO_2 emissions. This result is consistent with the findings of [72].

The empirical results about Eq. (8) are reported in Table 6, which shows that the per capita GDP has a positive and significant impact on trade openness for 7 countries out of 12. This implies that a 1 % increase in the per capita GDP increases trade openness within a range of 1.242 % (Switzerland) to 9.707 % (Japan). It has a negative significant impact on trade openness only for Canada. No significant relationship is found for the remaining countries. The panel result shows that the per capita GDP has a positive and significant impact on trade openness at 1 % level. The magnitude of 0.526 indicates that a 1 % increase in the per capita GDP increases trade openness by around 0.53 %. This result is consistent with the finding of [71]. Regarding the renewable energy consumption, we find that renewable energy consumption has a positive and significant impact on trade openness for 5 countries out of 12. Hence, a 1 % rise in the renewable energy consumption increases trade openness within a range of 0.227 % (the United Kingdom) to 2.109 % (Canada). Moreover, it has a negative and significant impact for France and Spain. This result is consistent with the findings of [19]. However, no significant relationship is found for the remaining countries. Renewable energy consumption has no significant impact on trade openness for the panel results. In addition, the coefficient of CO_2 emissions has a negative and significant impact on trade openness only for Japan and Portugal. Only, for Canada CO_2 emissions have a positive and significant impact on trade openness. But, no significant relationship is found for the remaining countries. Regarding the panel estimation, we find that the per capita CO_2 emissions have negative and significant impact on trade liberalization at 1 % level. The magnitude of 1.048 indicates that a 1 % increase in pollutant emissions decreases trade openness by around 1.048 %. This result is consistent with the findings of [2]. Finally, FDI has a positive and significant impact on trade openness for 3 countries out of 12. This implies that a 1 % increase in the FDI rate increases the foreign trade ratio to GDP within a range of 0.036 % (the Unites States) to 0.064 % (Canada). For the panel estimation, the coefficient of FDI is positive and significant at 1 % level. The magnitude of 0.159 implies that a 1 % increase in FDI increases trade openness by around 0.16 %. This result is consistent with the findings of [1].

3.1.2 Results for the middle-income countries

The empirical results about Eq. (5) presented in Table 7 show that renewable energy consumption has a statistically significant impact on the per capita GDP for 8 countries out of 12. It has a positive and significant impact on the per capita GDP for Algeria, Argentina, Brazil, Bulgaria and Chile. However, it has a negative and significant impact on the per capita GDP for China, Mexico and Turkey. For the remaining countries, no significant relationship is found. For the panel results, renewable energy consumption has a positive and significant impact on economic growth at 5 % level. The magnitude of 0.109 implies that a 1 % increase in renewable energy consumption increases economic growth by around 0.11 %. This result is consistent with the findings of [77]. In addition, the per capita CO_2 emissions have a negative and significant impact on the per capita GDP for Algeria. This seems to be consistent with the findings of [35]. However, CO_2 emissions have a positive and significant impact on the per capita GDP for 4 countries out of 12. This suggests that a 1 % increase in the CO_2 emissions increases economic growth within a range of 0.366 % (Bulgaria) to 1.355 % (Mexico). For the panel results, we find that the effect of the CO_2 emissions on economic growth is statistically significant at 1 % level. Moreover, trade openness has a significant positive impact on the per capita GDP for Algeria, China, Mexico and Turkey. However, for Argentina it has a significant negative impact. The panel estimation indicates that trade openness has a negative and significant impact on the per capita GDP at 1 % level. The magnitude of 0.720 implies that a 1 % rise in trade openness decreases economic growth by around 0.72 %. This result is in line with the findings of [46]. Finally, the coefficient of capital is positive and significant for 7 countries out of 12. But, no significant relationship is found for the remaining countries. For the panel results, this coefficient has a positive and significant impact on per capita GDP at 5 % level. This implies that a 1 % increase in capital increases economic growth by around 0.82 %. The result is consistent with the findings of [53].

The empirical results pertaining to Eq. (6) are given in Table 8. We find that real GDP has a positive and significant impact on renewable energy consumption for Argentina, Brazil, Bulgaria, Chile, and China. However, no significant relationship is found for the remaining countries. The panel result shows that the per capita GDP has a positive and significant impact on renewable energy consumption at 1 % level. The magnitude of 2.925 indicates that a 1 % increase in the per capita GDP increases renewable energy consumption by around 2.925 %. This result is consistent with the finding of [15]. Regarding the pollutant variable, we find that CO_2 emissions have a positive and significant impact on the demand of renewable energy for Colombia and Mexico. This implies that higher CO_2 emissions in these countries create demand for cleaner environment and encourage the use of renewable energy. In fact, a 1 % increase in pollution increases the share of renewable energy in the global mix by nearly 2.205, 0.849 %, in Colombia and Mexico, respectively. However, pollutant emissions have a negative impact on renewable energy for Argentina and Bulgaria. No significant relationship is found for the remaining countries. The panel result shows that CO_2 emissions have a negative impact at 1 % level. The magnitude of 8.380 indicates that a 1 % increase in CO_2 emissions increases renewable energy consumption by around

8.38 %. This result is consistent with the finding of [45]. Nevertheless, trade openness has a positive and significant impact on renewable energy consumption for Brazil and Bulgaria. On the other hand, it has a negative impact in Malaysia. For the panel result trade openness has a positive impact on renewable energy consumption at 1 % level. The magnitude of 4.190 implies that a 1 % increase in foreign trade increases renewable energy consumption by around 4.19 %. This result is in line with that of [65]. We also find that real oil price has a negative and significant impact on renewable energy demand for China and Mexico. However, no significant relationship is found for the remaining countries. The panel result shows that oil price has no significant relationship on renewable energy consumption. Finally, the coefficient of oil consumption has a statistically significant impact on renewable energy consumption for 4 countries out of 12. In fact, it has a positive impact in Bulgaria and Malaysia. However, it has a negative impact in Brazil and China. However no significant relationship is found for the rest of the countries. The panel estimation indicates that oil consumption has a positive and significant impact on renewable energy consumption at 1 % level.

The estimation results about Eq. (7) are reported in Table 9. It appears that the per capita GDP has a positive and statistically significant impact on CO_2 emissions for 5 countries out of 12. However, no significant relationship is found for the remaining countries. The panel result shows that the per capita GDP has a positive and significant impact on CO_2 emissions at 5 % level. The magnitude of 0.291 indicates that a 1 % increase in the per capita GDP increases CO_2 emissions by around 0.29 %. These results are consistent with the findings of [41]. Regarding the renewable energy consumption variable, it is found that renewable energy consumption has a statistically significant impact only for 2 countries out of 12. It has a negative impact on CO_2 emissions only for Bulgaria. However, for Malaysia, it has a positive and significant impact on CO_2 emissions. Whereas, for the remaining countries no significant relationship is found. For the panel results, no significant relationship is found. This result is consistent with the findings of [45]. The coefficient of trade openness has a negative and significant impact on pollutant emissions only for Venezuela. However, it has a positive and significant impact only for Thailand. For the remaining countries, no significant relationship is found. For the panel estimation, the coefficient of trade openness is positive and significant at 5 % level. The magnitude of 0.278 implies that a 1 % increase in trade openness increases CO_2 emissions by around 0.28 %. This result is consistent with the findings of [60]. On the other hand, the coefficient of urbanization has a negative and statistically significant impact on CO_2 emissions for Chile and Malaysia. For the remaining countries, and the panel estimation, no significant relationship is found. Finally, the coefficient of financial development has a statistically significant impact on pollutant emissions for 5 countries out of 12. It has a positive and significant impact for Chile, Colombia, and Malaysia, whereas it has a negative impact only for Bulgaria and China. For the remaining countries, and the panel estimation, no significant relationship is found.

The empirical results pertaining to Eq. (8) are given in Table 10. In this table, we present the impact of real GDP has a positive and significant impact on trade openness for Algeria, Colombia, Mexico and Turkey. This result is consistent with the finding of [17,71]. Moreover, the per capita GDP has a negative and significant impact on trade openness for Argentina. For the remaining countries, no significant relationship is found. For the panel estimation, the coefficient of per capita GDP is negative and significant at 1 % level. The magnitude of 0.766 implies that a 1 % increase in the per capita GDP decreases trade openness by around 0.77 %. However, the coefficient of renewable energy consumption is positive and significant on trade openness for Argentina and Thailand. On the other hand, it has a negative and significant impact on trade openness for China. For the remaining countries, no significant relationship is found. For the panel estimation, the coefficient of renewable energy consumption is positive and significant at 10 % level. The magnitude of 0.089 implies that a 1 % increase in renewable energy consumption increases trade openness by around 0.09 %. This result is consistent with the findings of Lean and Smyth, 2010. Moreover, the pollutant emissions have a statistically and significant impact on trade openness for 6 countries out of 12. Indeed, it has a positive and significant impact on trade openness for Argentina, China, and Malaysia. In addition, pollutant emissions have a negative and significant impact on trade openness for Algeria, Mexico and Venezuela. For the remaining countries, no significant relationship is found. For the panel estimation, the coefficient of CO_2 emissions is positive and significant at 1 % level. The magnitude of 3.457 implies that a 1 % increase in CO_2 emissions increases trade openness by around 3.46 %. This result complies with the findings of [2]. Finally, FDI have a positive and significant impact on trade openness for 4 countries out of 12. This implies that a 1 % increase in the FDI rate increases the level of trade openness within a range of 0.051 % (Malaysia) to 0.557 % (China). This result is consistent with the findings of [47]. However, for Argentina, it has a negative impact on trade openness. For the remaining countries and the panel result, no significant relationship is found.

4 Discussion

4.1 Discusses the empirical highlights for the high-income countries

Regarding the links between renewable energy and economic growth for individual cases, there is a positive unidirectional causality running from renewable energy consumption to economic growth in Canada, Switzerland and the UK. This indicates that, in these countries, increases in renewable energy consumption caused increases in economic growth, which implies that energy conservation policies that adversely impact renewable energy consumption may have an adverse effect on economic growth. This indicates the presence of the 'growth hypothesis'. Moreover, the positive effect of the use of renewable energy on economic growth further enhances the viability of the renewable energy sector, which provides an additional support for the assertion that renewable energy can serve as an important energy source for these countries. This is in line with the findings of [58,77]. No causality is found between renewable energy consumption and economic growth in Australia, France, Japan and Portugal, which demonstrates the 'neutrality hypothesis'. This finding means that energy conservation policies do not affect the income, and as such, they may be pursued without adversely affecting the real income (see [39,80]). This finding is in line with the results showed by [51]. In contrast, in Germany, Netherlands, Spain, Sweden and the US, there is a bidirectional causality between renewable energy consumption and economic growth. The presence of a bidirectional causality between renewable energy and economic growth lends support to the 'feedback hypothesis' whereby renewable energy consumption and economic growth are interdependent. This interdependency suggests that energy policies aimed at increasing the production and the consumption of renewable energy will have a positive impact on economic growth. This is in line with the results showed by (Apergis and Payne 2010,2012). We further find a positive a unidirectional causality running from CO_2 emissions to economic growth in the Netherlands. This result is consistent with the findings of [22,54]. In Spain, there is evidence of a positive unidirectional causality running from economic growth to CO_2 emissions. This result is in accordance with [29]. In contrast, no causality is found between CO_2 emissions and economic growth in Australia, Canada, France, Germany, Sweden, Switzerland, the UK and the US. This means that an increase in economic activity may be pursued without adversely affecting environmental quality. In addition, the adoption of a set of measures for environmental quality can be realized without pressure or adversely economic growth. However, the presence of a bidirectional causality between CO_2 emissions and economic growth has been supported in Japan and Portugal. These results are in line with the findings of [52]. Moreover, there is evidence of a positive unidirectional causality running from trade openness to economic growth in Netherlands. As a consequence, economic conservation measures that reduce economic activities may not have an adverse effect on trade openness aims. Besides, there is a causal unidirectional relationship running from economic growth to trade for France, Switzerland and the US. This indicates that economic conservation pressures that adversely have an impact on economic growth may have an adverse effect on trade openness, however, no causal relationship is found for Australia, Sweden, and the UK. Finally, a bidirectional causal relationship is found for Canada, Germany, Japan, Portugal and Spain. These results conform with the finding of [49]. Regarding the linkage between renewable energy consumption and CO_2 emissions, we find that there is evidence of a negative unidirectional causal relationship running from CO_2 emissions to renewable energy consumption in Canada, Spain and the UK. However, a positive unidirectional link is found for Sweden. Moreover, there is evidence of a negative unidirectional causal link running from renewable energy consumption to CO_2 emissions in Germany and the US. This implies that renewable energy consumption has a meaningful and crucial role in the reduction of pollutant emissions. Thus, there is evidence that is no causal link is found for Australia, France, Japan, the Netherlands, Portugal and Switzerland. These results are consistent with findings of Slim and Rafiq (2012). Concerning the linkage between trade openness and renewable energy consumption, there is a negative unidirectional causal relationship running from trade openness to renewable energy consumption in Germany and Netherlands. The presence of a positive unidirectional relationship running from renewable energy consumption to trade openness is found in Australia and Canada, but, a negative relationship in France. However, in Japan, Portugal and Switzerland no causal relationship is found. In Sweden and the UK, there is evidence of a bidirectional causality between trade openness and renewable energy consumption. This result is in line with the finding of [19]. Finally, looking at the causal linkage between trade openness and CO_2 emissions, we find a positive unidirectional causal relationship running from trade openness to CO_2 emissions for the US. Moreover, there is evidence of a unidirectional causal relationship running from CO_2 emissions to trade openness in Canada. In addition, there is evidence of no causal link in Australia, France, Germany, Netherlands, Spain, Sweden, Switzerland and the UK. Finally, there is evidence of a bidirectional causal relationship found for Japan and Portugal. This result is in line with the findings of [2].

Regarding the global panel, the findings reveal that there is a bidirectional causality between renewable energy consumption and economic growth. This is in line with the result found by Apergis and Payne 2012. The presence of a bidirectional causality between renewable energy and economic growth lends support to the 'feedback hypothesis' whereby renewable energy consumption and economic growth are interdependent. This interdependency suggests that energy policies which aim at increasing the production and the consumption of renewable energy will have a positive impact on economic growth. The presence of a bidirectional causality between CO_2 emissions and economic growth. This result is in line with the findings of [52]. In addition, we find that the existence of a bidirectional causality between trade openness and economic growth. This result is consistent with the finding [49]. Regarding the linkage between renewable energy consumption and CO_2 emissions, we find that there is evidence of a bidirectional causal link. Moreover, there is a unidirectional causal link running from trade openness to renewable energy consumption. This result is in line with the finding of [19]. Finally, looking at the causal linkage between trade openness and CO_2 emissions, we find a positive unidirectional causal relationship running from CO_2 emissions to trade openness. This result is in line with the findings of [2]. These results are summarized in the Fig. 1 below.

4.2 Discusses the empirical highlights for the middle-income countries

Regarding the links between renewable energy and economic growth for individual cases, there is a positive unidirectional causality running from renewable energy con-

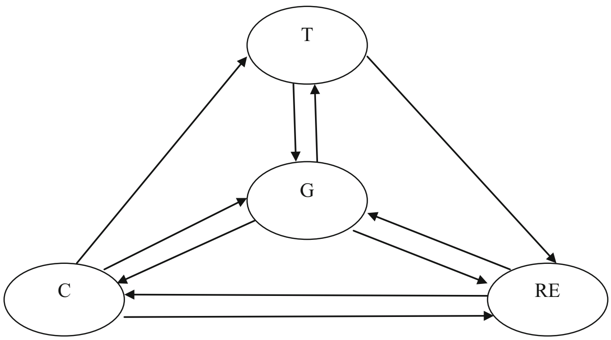

Fig. 1 The four-way linkages for the high-income countries

sumption to economic growth in Algeria, Mexico, and Turkey. This indicates that, energy conservation policies that adversely impact renewable energy consumption may have an adverse effect on economic growth. This indicates the presence of the 'growth hypothesis'. This is in line with the findings of [58]. However, no causality is found between renewable energy consumption and economic growth for Colombia, Malaysia, Thailand, and Venezuela, which postulates the 'neutrality hypothesis' for renewable energy consumption. This finding is similar with the results showed by [51]. In contrast, in Argentina, Brazil, Bulgaria, Chile, and China, there is evidence of a bidirectional causality between renewable energy consumption and economic growth. The presence of a bidirectional causality between renewable energy and economic growth lends support to the 'feedback hypothesis'. This is in line with the results showed by Apergis and Payne 2012. We further find a positive unidirectional causality running from CO_2 emissions to economic growth in Algeria and Brazil. This implies that, in this country, increases in CO_2 emissions caused increases in economic growth. This result is consistent with the findings of [22]. In Colombia there is evidence of a positive unidirectional causality running from economic growth to CO_2 emissions implying that increases in economic growth caused increases in pollutants emissions. This result is similar with that of [29]. In contrast, no causality is found between CO_2 emissions and economic growth in Chile, China, Malaysia, Thailand, Turkey, and Venezuela. This means that an increase in economic activity may be pursued without adversely affecting environmental quality. Moreover, the adoption of a set of measures for environmental quality can be realized without pressure or adversely economic growth. However, the presence of a bidirectional causality between CO_2 emissions and economic growth has been supported in Argentina, Bulgaria and Mexico. These results are in line with the findings of [52]. On the other hand, there is evidence of a positive unidirectional causality running from trade openness to economic growth in China. As a result, economic conservation measures that reduce economic activities may not have an adverse effect on trade openness. In addition, we find a causal unidirectional relationship running from economic growth to trade openness for Colombia. This implies that economic conservation pressures that have adversely impact on economic growth may have an adverse effect on trade openness. However, no causal relationship is found for Brazil, Bulgaria, Chile, Malaysia, Thailand, and Venezuela. Finally, a bidirectional causal relationship found for Algeria, Argentina, Mexico, and Turkey. These results are consistent with the finding [2]. Regarding the linkage between renewable energy consumption and CO_2 emissions, we find that there is evidence of a negative unidirectional causal relationship running from CO_2 emissions to renewable energy consumption in Argentina. Nevertheless, a positive unidirectional link running form CO_2 emissions to RE is found for Colombia and Mexico. Moreover, there is evidence of a unidirectional causal link running from renewable energy consumption to CO_2 emissions in Chile and Malaysia. However, the presence of a bidirectional causality between CO_2 emissions and renewable energy consumption has been supported in Bulgaria. Therefore, there is evidence of no causal link for Algeria, Brazil, China, Thailand, Turkey, and Venezuela. These results are consistent with findings of [66]. Concerning the linkage between trade openness and renewable energy consumption, we find the presence of a negative unidirectional causal relationship running from trade openness to renewable energy consumption in Malaysia, while a positive relationship is found for Brazil, and Bulgaria. A positive unidirectional relationship running from renewable energy consumption to trade openness is found for Argentina and Thailand. In contrast, in Algeria, Chile, Colombia, Mexico, Turkey and Venezuela, there is evidence that no causal relationship found. In China, there is evidence of a bidirectional causality between trade openness and renewable energy consumption. This result is in line with the finding of [19]. Finally, by looking at the causal linkage between trade openness and CO_2 emissions, we find a positive unidirectional causal relationship running from CO_2 emissions to trade openness for Algeria, Argentina, China, Malaysia, and Mexico. In addition, there is evidence of no causal link in Brazil, Bulgaria, Chile, Colombia, Thailand and Turkey. Finally, there is evidence of a bidirectional causal relationship for Japan and Portugal. This result is in line with the finding of [60].

Regarding the middle-income panel, the findings reveal that there is a bidirectional causality between renewable energy consumption and economic growth. This is in line with the result found by [77]. The presence of a bidirectional causality between CO_2 emissions and economic growth. This result is in line with the findings of [52]. In addition, there is evidence of a bidirectional causality between trade openness and economic growth. This result is consistent with the finding of [49]. Regarding the linkage between renewable energy consumption and CO_2 emissions, we find that there is evidence of a negative unidirectional causal link, running from renewable energy consumption to CO_2 emission, which supports the findings of [13]. Moreover, we find a bidirectional causal link between trade openness and renewable energy consumption. This result is in line with the finding of [19]. Finally, looking at the causal linkage between trade openness and CO_2 emissions, we find a bidirectional causal relationship running from CO_2 emissions to trade openness. This result is in line with the findings of [2]. These results are summarized in the Fig. 2 below.

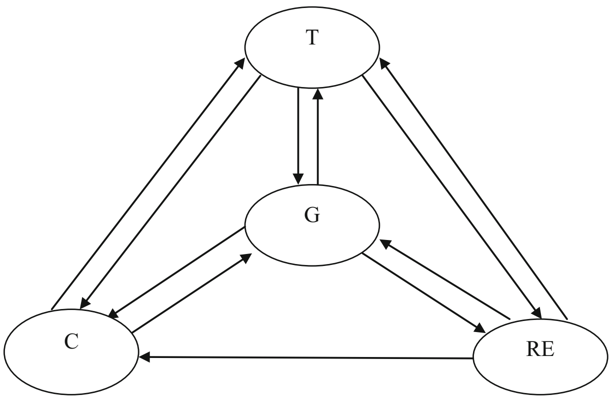

Fig. 2 The four-way linkages for the middle-income countries

5 Conclusions and policy implications

The aim of the present study is to examine the four-way linkages between renewable energy, CO_2 emissions, trade openness, and economic growth using simultaneous-equation panel data models for 24 countries over the period 1990–2011. However, to the best of our knowledge, none of the empirical studies focused on the investigation of the four-way linkages between these variables in a comparative framework between high- and middle-income countries via the simultaneous-equation panel data models.

Our results for the high-and middle-income subpanels can be summarized as follows. For the high-income countries, the highlights reveal that there is a bidirectional causality between renewable energy consumption and economic growth. Further, there is a bidirectional causality between CO_2 emissions and economic growth. In addition, we find that the existence of a bidirectional causality between trade openness and economic growth. Regarding the linkage between renewable energy consumption and CO_2 emissions, we find that there is evidence of a bidirectional causal link. Moreover, there is a unidirectional causal link running from trade openness to renewable energy consumption. Finally, looking at the causal linkage between trade openness and CO_2 emissions, we find a positive unidirectional causal relationship running from CO_2 emissions to trade openness.

On the other hand, our highlights for the middle-income countries support the evidence of a bidirectional causality between renewable energy consumption and economic growth. Furthermore, there is a bidirectional causality between CO_2 emissions and economic growth. In addition, there is evidence of a bidirectional causality between trade openness and economic growth. Regarding the linkage between renewable energy consumption and CO_2 emissions, we find that there is evidence of a negative unidirectional causal link, running from renewable energy consumption to CO_2 emission. Moreover, we find a bidirectional causal link between trade openness and renewable energy consumption. Finally, we find a bidirectional causal relationship between CO_2 emissions to trade openness.

These insights have varied implications on policy instruments to manage the dynamics among these key variables. The interdependence between renewable energy consumption and economic growth suggests that energy policies designed to increase the production and consumption of renewable energy will have a positive effect on economic growth. Moreover, the environmental quality can negatively affect productivity by affecting human health. In addition, given the reduction in the emissions of air pollution and greenhouse gases associated with renewable energy, there is also a positive spillover to the environment. Indeed, international trade with its positive impact on technology transfer can greatly help the middle-income countries to diffuse the adoption of production technologies using renewable energy, and building the human, technological and financial capacities in order to establish the renewable energy technologies, and to promote their share in the global mix in order to keep a clean environment. As a crucial recommendation, middle-income countries with the help of the high-income ones should to reduce the legal and institutional barriers in order to improve the international exchange as well as enhance the use of renewable energy sources through financial incentives, access to emerging technologies, and technical expertise in the development and assessment of the renewable energy sector. Furthermore, fiscal incentives (emissions taxes, pollution permits, subsidies etc.) should be important enough to induce producers to use renewable energy, because abandoning a polluting technology for a green technology still needs important investments, and also realize economies of scale that attract private sector investments especially in middle-income countries. Finally we recommend, both high-and-middle income countries to build a partnership with the international organization and between themselves in order to promote research and development in renewable energy technologies, and boost innovation, to realize economies of scale that attract private sector investments and effectively develop the PPP (i.g. Public-private partnership).

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